APPLIED ELECTRICITY

VOL. III

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APPLIED ELECTRICITY

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त्वदीयं वस्तु गोविन्द तुभ्यमेव समर्पये ।

श्रीकृष्णार्पणमस्तु ।

PREFACE TO THE SECOND EDITION.

In issuing this revised edition, it has been desirable to enlarge it considerably beyond its original limits.

It is primarily intended for the students of the B.Sc. Engineering classes of the Benares Hindu University.

Academic training is certainly essential if the students have to have a fair chance in climbing to the top of their profession. Hence the theoretical side of the subject has been adequately dealt with, so that they may comprehend the principles underlying the process in which they are engaged, and may be able to see reasons for many of the operations they are called upon to perform.

But the young graduates in the practical field are always more or less suspects of their fellow workers, and probably never really see anything of the atmosphere in which the normal apprentice would spend some years of his life. To help my students and young engineers, practical hints regarding erection, operation, care and management have been given along with theory which would be of immense help to them after their College career.

In the preparation of the theoretical side of this book I have necessarily drawn freely from all sources ot information and among many, the works of Messrs J. W. Mears & R. E. Neale, C. E. Magnusson, H. Waddicor, William T. Taylor, A. T. Painton, Frank F. Fowle Chief Editor of the Standard Handbook for Electrical Engineers and Harold Pender Chief Editor, Handbook for Electrical Engineers deserve special mention, besides other works which have been acknowledged in the text in due places.

The Practical notes have been taken from the Bombay Electric Tramway & Supply Company, The Tata Hydro-Electric Works, The Cauvery Falls Scheme at Sivasamudram and all other important Electrical Installations all over India.

Instruction-books supplied by the manufacturers for the working of the electrical equipments of these installations have been freely consulted, such as those of Messrs. Metropolitan Vickers, General Electric Company, Brown Boveri and others.

It is extremely difficult to acknowledge indebtedness to all the different sources in a work of this kind and I must content myself with saying that I have benefitted largely from most of the Existing text books, technical journals, standard works on the subject and manufacturers' notes and instructions.

However, in some instances, search for the Original has proved futile, and apologies are made to all authors and publishers who may find their works used without any definite reference, such omission being unintentional.

My grateful acknowledgment is due to all the above authors, their publishers, and manufacturers.

I have great pleasure in acknowledging with thanks the help I have received from Prof. P. C. Dutt, B. Sc., (Eng.) and Mr. B. G. Ghate, B. Sc.,(Eng.), both my pupils, during the revision of this work.

The last stages of revision of the book were undertaken under the stress of a great domestic bereavement, but I trust no serious flaws have passed undetected. If the book contains errors, I shall be grateful to any reader who will point them out.

Engineering College,
Mahastami,
October 5, 1935.

B. C. Chatterjee.

PREFACE TO THE FIRST EDITION.

This volume is the continuation of the author's Elements of Applied Electricity. The first volume dealt with general theory, the second with generation, and the present one deals with the transmission, distribution and storage of Electrical Power from the point of view of the Executive Engineer rather than that of the manufacturer. An endeavour has been made to offer solutions for almost every difficulty which a Superintendent of an Electric Plant is likely to meet with. But the author will be grateful to readers who will point out any errors or omissions.

In addition to the authorities quoted in the preface to the first and second volumes, the author offers his grateful acknowledgments to the following :—

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Benares Hindu University, B. C. Chatterjee

April 25, 1924.

CONTENTS.

APPLIED ELECTRICITY

CHAPTER I

NETWORKS

1. We have shown, in detail, the solution of circuits containing resistance, inductance and capacitance in the previous sections (*vide* Vol. II, the last chapter). We now propose to solve the problems on distribution network which very often confront the engineers in the calculation of cross-sections of lines for the distribution networks. A few examples added below will clearly show the method of procedure. The basis of the calculation has been (*i*) that the maximum permissible potential drop should not exceed a given limit established by the law, (*ii*) the maximum IR drop from the feeding point should be nearly the same up to all the null points in a given network.

The two important principles that have been used for the calculation are—

(*i*) Ohm's Law. $I = E/R$.
(*ii*) Kirchhoff's Laws—(*a*) $\Sigma I = 0$ at any point.
(*b*) $\Sigma IR = 0$ in any closed path or mesh.

2. Drop in a conductor supplied from both ends.

Example 1. Let AB be a conductor receiving current at equal pressures at each end; 5 and 10 amperes, respectively, are taken off at distances as indicated on the diagram 10·1. Find the current at A and B, and that flowing from C to D.

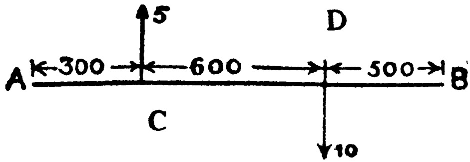


Fig. 1·01

Solution—

Total current flowing into portion of conductor shown $= 5 + 10 = 15$ amps.

Let x amps. be supplied at A.

Then $15-x$ amps. are supplied at B.

Then drop of potential between A and C must be equal to that between B and C.

$\therefore$ If r = resistance per yard of conductor,

$$x \times 300\,r = (15 - x)\,500\,r + (15 - x - 10)\,600\,r\,;$$

$$\therefore\ x\,(300\,r + 500\,r + 600\,r)$$
$$= 15 \times 500\,r + 15 \times 600\,r - 10 \times 600\,r\,;$$

$$i.e.,\ x = \frac{7{,}500 + 9000 - 6.000}{1{,}400} = \frac{10{,}500}{1{,}400} = 7{\cdot}5 \text{ amps}$$

hence, 7·5 amps. are supplied at A,
and 7·5 amps. are supplied at B,
also current in CD is 2·5 amps. flowing from C to D.

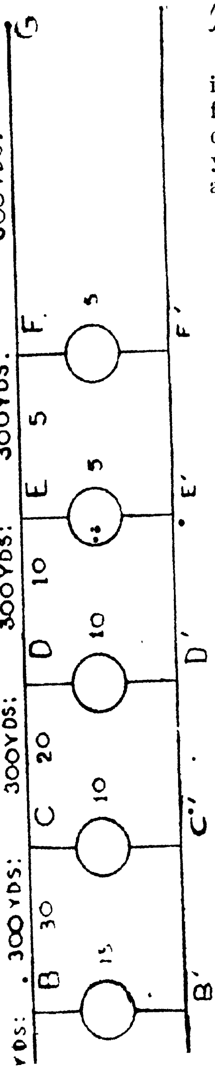


Fig. 1·02

Example 2. The feeding point is at AA' and the voltage at the feeding point is 240 volts. Loads during the peak load time of the year at different points are in amperes and the supply is D. C.

1/0 S. W. G. is used for the line.

Whose A = ·08245 sq. in,

R = ·2912 ohm per 1000 yds. at 60° F.

Maximum temperature of the wire = 149° F and temperature correction for the increase of resistance is 1·2.

Find the minimum voltage at different points.

Solution –

Resistance of the conductor at 149° F.

$= {\cdot}2912 \times 1{\cdot}2$

$= {\cdot}34944$ ohm per 1000 yds.

Voltage across BB' $= 240 - 2\ (300/1000) \times {\cdot}34944 \times 45$

$= 240 - 9{\cdot}45$

$= 230{\cdot}55$ volts.

Voltage across CC' $= 230{\cdot}55 - 2\ (300/1000) \times {\cdot}34944 \times 30.$

$= 230{\cdot}55 - 6{\cdot}30$

$= 224{\cdot}25$ volts.

Voltage across DD' $= 224{\cdot}25 - 2\ (300/1000) \times {\cdot}34944 \times 20$

$= 224{\cdot}25 - 4{\cdot}2$

$= 220{\cdot}05$ volts.

Voltage across EE' $= 220{\cdot}05 - 2\ (300/1000) \times {\cdot}34944 \times 10$

Voltage across FF$'$ $= 217{\cdot}95 - 2\ (300/1000) \times {\cdot}34944 \times 5$

$= 217{\cdot}95 - 1{\cdot}05$

$= 216{\cdot}9$ volts.

Example 3. The distribution line in example 2 is fed from both ends AA$'$ and GG$'$ with the same voltage of 240 volts. Find the minimum voltage across each load.

Let x amperes be flowing from A.

Then $[300\,x + 300\,(x-15) + 300\,(x-25) + 300\,(x-35) + 300\,(x-40) + 600\,(x-45)]\ {\cdot}34944 \times 2/1000 = 0$

Or, $2100\,x - 61500 = 0$

Or, $x = 29{\cdot}3$ amperes.

Hence, voltage across BB$'$ $= 240 - 2\ (300/1000) \times {\cdot}34944 \times 29{\cdot}3$

$= 240 - 6{\cdot}15$

$= 233{\cdot}85$ volts.

Voltage across CC$'$ $= 233{\cdot}85 - 2\,(300/1000) \times {\cdot}34944 \times 14{\cdot}3$

$= 233{\cdot}85 - 2{\cdot}803$

$= 231{\cdot}047$ volts.

Voltage across DD$'$ $= 231{\cdot}047 - 2\ (300/1000) \times {\cdot}34944 \times 4{\cdot}3$

$= 231{\cdot}047 - {\cdot}903$

$= 230{\cdot}144$ volts.

Voltage across EE$'$ $= 230{\cdot}144 + 2\ (300/1000) \times {\cdot}34944 \times 5{\cdot}7$

$= 230{\cdot}144 + 1{\cdot}197$

$= 231{\cdot}341$ volts.

Voltage across FF$'$ $= 231{\cdot}341 + 2\ (300/1000) \times {\cdot}34944 \times 10{\cdot}7$

$= 231{\cdot}341 + 2{\cdot}247$

$= 233{\cdot}588$ volts.

Example 4. Solve the example 2 with the feeding point voltage at AA$'$ = 240 volts and at GG$'$ = 235 volts.

Then $(2100\,x - 61500)\ {\cdot}34944 \times 2/1000 = 5$

Or, $x = 32{\cdot}7$ amperes.

Then, find the voltage across the loads as in example 2.

3. Drop in uniformly-loaded line.

(*a*) A uniformly-loaded distributor fed at one end gives a total drop equal to that produced by the whole of the load supposed to be concentrated at the mid-point.

Let i = current tapped from each unit length,

r = resistance per unit length.

The drop at distance x from F

$= \Sigma$ (moments up to x) + moments of the whole load beyond x assumed acting at x.

$$= \int_0^x i\, r\, x\, d x + i\,(l-x)\, r\, x$$

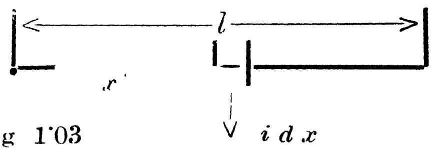


Fig 1·03

$$= \tfrac{1}{2}\, i\, r\, x^2 + i\, r\, l\, x - i\, r\, x^2$$

$$= i\, r\, l\, x - \tfrac{1}{2}\, i\, r\, x^2 \text{ at the far end } x = l$$

Hence, drop $= \frac{1}{2}\, i\, r\, l^2 = \frac{1}{2}\,(i\, l) \times (l\, r) = \frac{1}{2}\, I\, R$

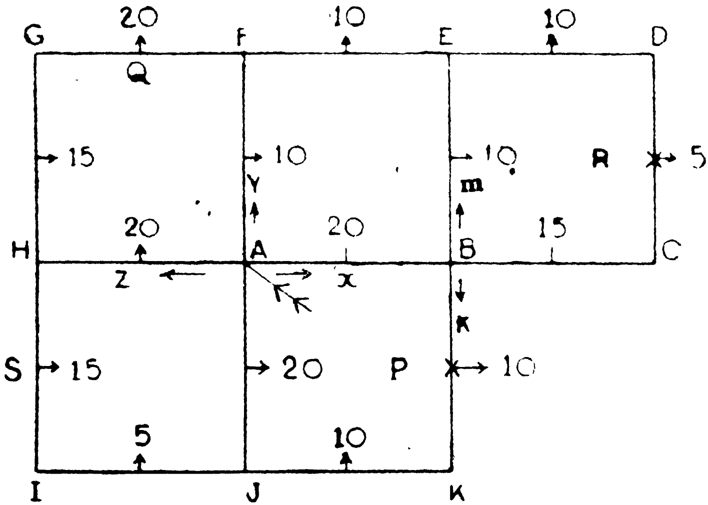
(*b*) If the distributor is fed at both ends with the same voltage of supply, the minimum potential is evidently at the mid-point, and we may imagine two uniformly-loaded distributors fed at one end, the resistance of each is $\frac{R}{2}$ and the total load current $= \frac{I}{2}$ in each.

Hence, the drop at the mid-point

$$= \tfrac{1}{2}\, \frac{I}{2} \times \frac{R}{2} = \frac{1}{8}\, I\, R.$$

Example 5

Fig 1·04



Let ABCDEFGHIJK be the plan of the roads in a typical city. The area is to be supplied by 3-wire D.C. mains. The figures at the arrow heads represent the current in the outers, assuming balanced load. Assume that the load of any particular road is uniformly distributed and all roads are of equal length (AB=BC==CD=DE=EF=FG=......900 yds.).

The feeding point is at A, and the voltage at that point is 480 volts across outers.

The cross-sectional area of the outer conductor of the whole network is 1/0 S. W. G. (A=·08295 sq. in having R=·36144 ohm per 1000 yds. at the maximum working temperature.

Find (1) the point of maximum drop in network.

(2) the voltage at the point of maximum drop.

Solution—

Consider the network representing the plan of positive line. The current will be flowing from the feeding point towards the point of maximum drop.

Then—

Considering the loop ABEFA

$[x+(x-20)+m+(m-10)+(x-k-60)+(x-k-70)-(y-10)-y]\ 900/2=0$

Or, $4x-2y-2k+2m-150=0$ ... (1)

Considering the loop BCDEB

$[(x-m-k-20)+(x-k-m-35)\ 2+(x-k-m-40)\ 2+(x-m-k-50)-(m-10)-m]\ 900/2=0$

Or, $6x-6k-8m-210=0$ ... (2)

Considering the loop AFGHA

$[y+(y-10)+(x+y-k-80)+(x+y-k-100)\ 2+(x+y-k-115)-(z-20)-z]\ 900/2=0$

Or, $4x+6y-2z-4k-385=0$ ... (3)

Considering the loop AHIJA

$[z+(z-20)+(x+y+z-k-135)+(x+y+z-k-150)\ 2+(x+y+z-k-155)+(x+y+z-175)+(x+y+z-195)]$

$$\times\frac{900}{2}=0$$

Or, $6x+6y+8z-4k-980=0$.........(4)

Considering the loop ABKJA

$[x+(x-20)+k+(k-10)2+(k-20)+(x+y+z-175)+(x+y+z-195)]\ \dfrac{900}{2}=0$

Or, $4x+2y+2z+4k-430=0$.........(5)

Solving the equations 1, 2, 3, 4, and 5 we have—

$x=56{\cdot}2$ amperes.
$y=45{\cdot}6$ „
$z=48{\cdot}3$ „
$k=4{\cdot}2$ „
$m=12{\cdot}75$ „

Hence, we see that there are several points P, Q, R and S where the current changes sign.

Then—

$$\Sigma \text{ ampere yds. per line up to } P=96{\cdot}6\times\frac{900}{2}$$

$$\text{„ „ „ „ } Q=98{\cdot}8\times\frac{900}{2}$$

Σ ampere yds. per line up to R $= 121{\cdot}15 \times \frac{900}{2}$

" " " " S $= 87{\cdot}5 \times \frac{900}{2}$

Hence, the point of maximum drop is R.

Σ I R from feeding point up to R (both lines)

$$=121{\cdot}15 \times \frac{900}{2} \times 2 \times \frac{{\cdot}36144}{1000}$$

$=$ 39·4 volts.

Voltage across outer at the point of maximum drop

$=480-39{\cdot}4=440{\cdot}6$ volts.

Example 6. Solve example 4 with the assumption that the supply is 3-wire single-phase A. C. The average p f. of load is ·9 and the reactance = ·2616 ohm per 1000 yds. at 50 cycles per sec.

Solution—

Σ I R up to the point of maximum drop

$=39{\cdot}4$ volts.

Σ I X up to the point of maximum drop

$$=121{\cdot}15 \times \frac{900}{2} \times 2 \times \frac{{\cdot}2616}{1000}$$

$=28{\cdot}4$ volts.

Let V be the voltage at the point of maximum drop across outers.

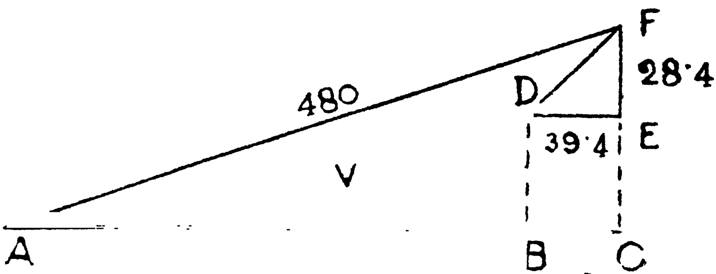


Fig. 1·05

$$\text{Then, } (480)^2 = (V \times \cdot 9 + 39\cdot 4)^2 + (V \times \cdot 436 + 28\cdot 4)^2$$

$$= \cdot 81V^2 + 2V \times \cdot 9 \times 39\ 4 + (39\cdot 4)^2$$

$$+ (\cdot 436)^2 \ V^2 + 2 \times \cdot 436 \times 28\cdot 4V + (28\ 4)^2$$

Whence, $V = 432\cdot 1$

4. Solution of circuit by trial and error method.

When a network has got large number of loops, it is a lengthy process to solve it by means of simultaneous equations. There will be as many unknown figures as there are number of loops and to get the values of those unknown figures there will be equal number of simultaneous equations Such a network can be solved in a

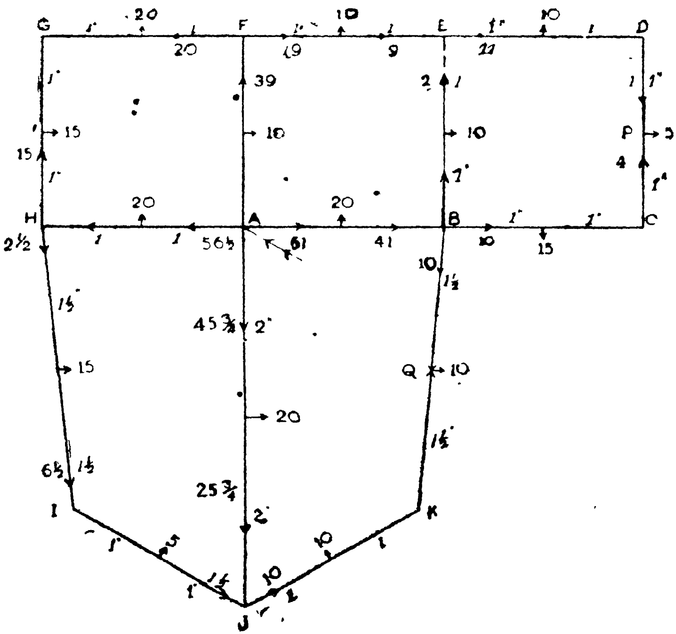


Fig 1·06.

shorter time by trial. The trial method is easy for him who has got good judgment. With less amount of good judgment there is a possibility of greater trouble. The main consideration in the trial method is to judge the point of maximum drop in the network. If the point of maximum drop be judged, then the solution will be easy.

The following example will give an idea of the trial method :—

Feeding point is at A. Figures at the arrowheads represent the load current in amperes—Fig. 1·07.

Scale 1″ = 600 yards.

The supply being 3-wire D. C and the voltage across outers at the feeding point = 480 volts.

The load is balanced. The area of the outer conductor= ·08295 sq. in. (1/0 S W. G.) having R = ·36144 ohm per 1000 yds. at the maximum working temperature.

Find the voltage at the point of maximum drop.

Now assuming one null point at P and another at Q, we can proceed to solve the network.

Consider first that the load 5 amp. at P will be supplied with 4 amp from the side C and 1 amp. from D and also the load of 10 amp. at Q be totally supplied from B. Then proceed to solve the rest of the network.

According to Kirchhoff's Law—

$\Sigma\, i\, l$ from B to P via C must be equal to

$\Sigma\, i\, l$ from B to P via E and D.

Similarly. $\Sigma\, i\, l$ of A B E = $\Sigma\, i\, l$ of A F E.

In this way coming up to the last loop AJKB we see that our assumptions are wrong.

For correct solution—

Current coming towards J must be equal to the current going away from J. But we find that the current going away from J is much less.

Next, assume that 8 amperes are coming towards Q from B.

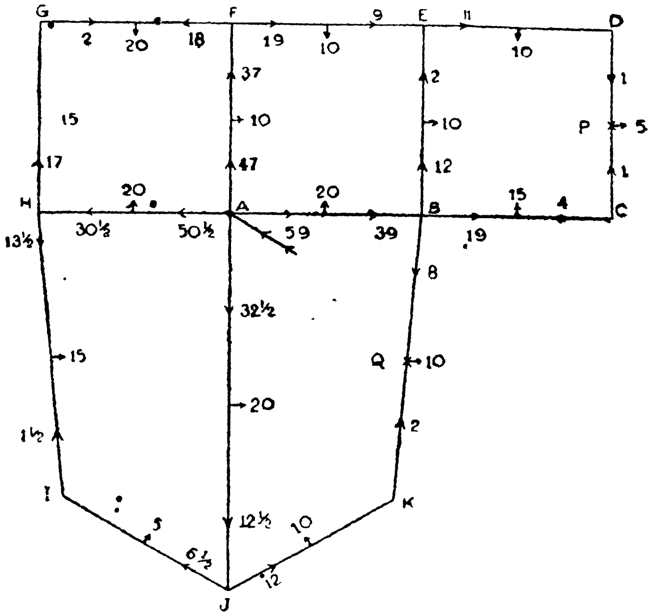


Fig. 1·07

In this we find that the current going away from J is greater than that coming towards J.

The solution will be correct if instead of 8 amperes flowing from B to Q is assumed in between 8 and 10 amp.

Next, assume $8\frac{1}{2}$ amp. flowing from B towards Q.

Now the solution is almost correct.

There are several points (P, Q, R and S) where current changes sign Fig. 1·08.

Σ ampere yds. per line up to	P = 126	× 600
,, ,,	Q = 111·75	× 600
,, ,,	R = 108·5	× 600
,, ,,	S = 103·5	× 600

The voltage at P can be found by the previous method.

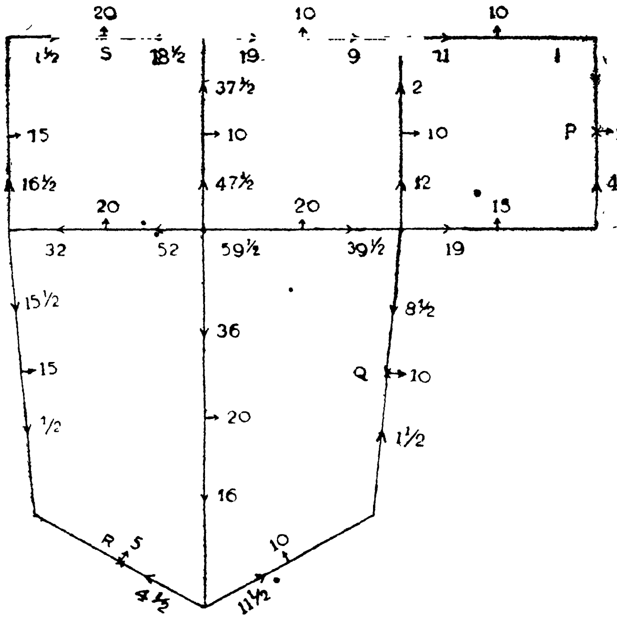


Fig. 1·08

5. The method of elimination.

Example. A network of 3-phase A. C. is as shown here in Fig. 1·09, which on elimination is represented as in Fig. 1·10, next page.

[Load in kW. and distances in inches linear scale being 1″ = 1,200 ft.]

Then, we proceed with the solution as follows :—

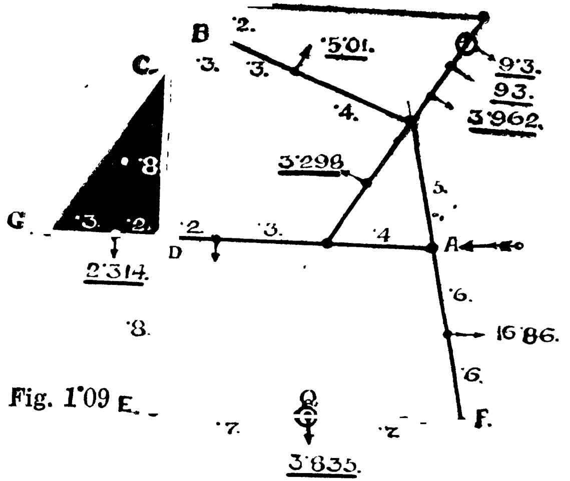


Fig. 1·09

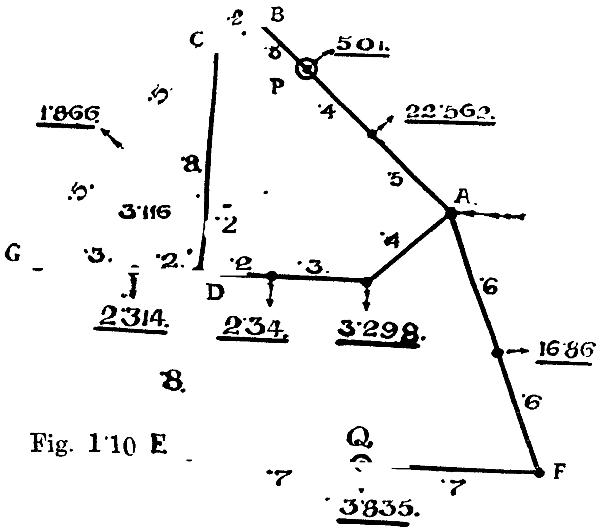


Fig. 1·10

Circuit ABCDA :—

$x \times \cdot 5 + (x - 22\cdot 562) \times \cdot 4 + (x - 27\cdot 572) \times \cdot 5 + (x - y - 27\cdot 572) \times \cdot 8 + (x - y - 30\cdot 688) \times \cdot 2 + (x + z - 55\cdot 513) \times \cdot 2 + (x+z - 57\cdot 877) \times \cdot 3 + (x + z - 61\ 175) \times \cdot 4 = 0$ ... ... (1)

Circuit CGD = Circuit CD :—

Or, $y \times \cdot 5 + (y - 1\cdot 866) \times \cdot 8 + (y - 4\cdot 18) \times \cdot 2 = (x - y - 27\cdot 572) \times \cdot 8 + (x - y - 30\cdot 688) \times \cdot 2$ ... (2)

Circuit AFEDA :—

$z \times \cdot 6 + (z - 16\cdot 86) \times 1\cdot 3 + (z - 20\cdot 695) \times \cdot 15 + (x + z - 55\cdot 513) \times \cdot 2 + (x + z - 57\cdot 877) \times \cdot 3 + (x + z - 61\cdot 175) \times \cdot 4 = 0$ ... ... (3)

Or, $3\cdot 3\, a - y + \cdot 9z - 103\cdot 94 = 0$ ... ... (1)

$x - y - 28\cdot 195 = 0$ ... ... (2)

$9x + 4\cdot 3z - 105\cdot 89 = 0$ ... ... (3)

Solving these equations—

$x = 25\cdot 356$

$y = -2\cdot 839$

$z = 19\cdot 32$

Σ kW. ft. up to P (null point)

$= 13\cdot 7956 \times 1200$

$= 16554$

Σ kW. ft up to Q (null point)

$= 14\cdot 79 \times 1200$

$= 17748$

Σ kW. ft. up to R in the radial line

$= 14\cdot 14 \times 1200$

$= 16970$

We take the average value

$= 17000$

Σ amp. ins. per line

$$= \frac{17000 \times 12 \times 1000}{3 \times 115 \times 0\cdot 9}$$

$= 657000$

$$\therefore \text{ area of cross-section } A = \frac{657000 \times \cdot 7 \times 10^{-6} \times 100}{7 \times 115}$$

$= 0\cdot 05714$ sq. in.

Where per cent. drop = 7 % of declared voltage of 115 volts between lines ;

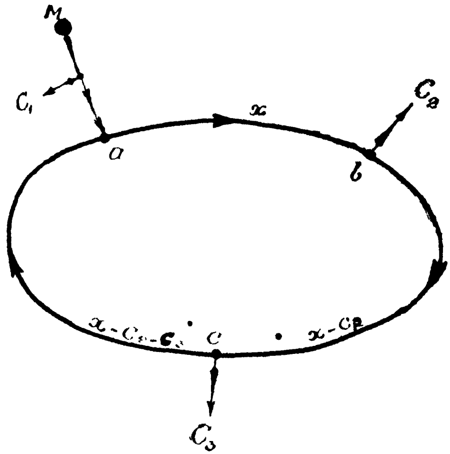
and $0\cdot 9$ = Power factor of the load.

6. Loop fed from one centre.

Let us consider the loop of a line as shown in Fig. 1·11. Let M be the feeding point and let the values of the currents be as marked in the diagram. Now we have—

$$(\rho/S)\left\{ l_1 x + l_2 (x - C_2) + l_3 (x - C_2 - C_3) \right\} = 0 \quad [(1)$$

$$Or,\ x = \left\{ l_2 C_2 + l_3 (C_2 + C_3) \right\} \Big/ (l_1 + l_2 + l_3) \quad (2)$$



. Fig. 1·11

Where l_1, l_2 and l_3 are the lengths of ac, cb and ba, respectively.

Let us suppose that this value of x is less than C_2. In this case the potential will have its minimum value at C, and the potential drop between M and C will be p. Let p_1 be the P. D. between M and a. Then if S be the

*Adopted from "The Theory of Electric Cables and Networks," by Principal Alexander Russel, M. A., D. Sc.

section of the main Ma and S_1 be the section of the line forming the loop we have—

$$S = \left\{ d\, C_1 + l\,(C_2 + C_3) \right\} \Big/ 30\, \rho_1 \qquad \ldots \quad (3)$$

$$\text{and } S_1 = l_1\, x \Big/ 30\,(p - p_1) \qquad \ldots \quad (4)$$

Where l is the length of the main Ma, and d is the distance of the feeding centre for C_1 from M. Hence, if V be the volume of the copper used in the main Ma and in the loop abc, we have—

$$V/2 = l\,S + (\,l_1 + l_2' + l_3\,)\; S_1 \qquad \ldots \quad (5)$$

$$= \frac{m}{p_1} + \frac{n}{p - p_1}$$

$$\text{where, } m = l \left\{ d_1\; C_1 + l\,(C_2 + C_3\,) \right\} /30 \;\ldots\; (7)$$

$$\text{and } n = l_1 \left\{ l_2\; C_2 + l_3\,(\,C_2 + C_3\,) \right\} /30 \ldots (8)$$

Now m, n, and p are independent of the values of the sections of the mains, and hence, by the differential calculus, V will have its extreme values when—

$$O = -\frac{m}{p_1^2} + \frac{n}{(p - p_1\,)^2} \qquad \ldots \qquad \ldots \quad (9)$$

$$\text{and when } p_1 = p/ \left\{ 1 + \sqrt{n/m} \right\} \qquad \ldots \; (10)$$

The volume of the copper employed in the mains has its minimum value. Having found the value of p_1 the value of S and S_1 can be readily found out from the above equations.

*7. Loop with several feeding centres.

In the loop, (Fig. 1·12), let L, N, O and M be the feeding centres, which, we suppose, are all maintained at the same potential.

Let x be the current in Ma_1 and let currents C_1, C_2 and C_3 be tapped from the loop at points a_1, b_1 and c_1 between M and L. Then if $Ma = l_1$, $ab = l_2$, $bc = l_3$ and $cL = l_4$, we have—

$$xl_1 + (x - C_1)\, l_2 + (x - C_1 - C_2)\, l_3 + (x - C_1 - C_2 - C_3)\, l_4 = 0$$

$$Or,\ x = \frac{\left\{ C_1 (l_2 + l_3 + l_4) + C_2 (l_3 + l_4) + C_3\, l_4 \right\}}{l_1 + l_2 + l_3 + l_4} = 0$$

If the value of x found from this equation be less than C_1, a will be the point of minimum potential. If x be greater than C_1, but less than $C_1 + C_2$, b will be the point of minimum potential, and if x be greater than $C_1 + C_2$, c will be the point of lowest potential between L and M. Let us first suppose that x is less than C_1. In this case. $S = l_1\, x/30$ p.

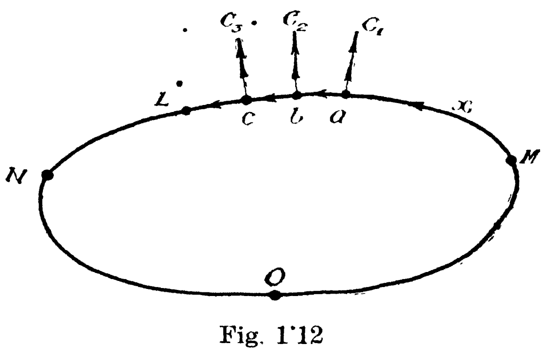


Fig. 1·12

If the value of x lies between C_1 and $C_1 + C_2$, the section of the loop between M and L would be given by

$$S = \left\{ l_1 x + l_2 (x - C_1) \right\} / 30\, p_1$$

and when the value of x is greater than $C_1 + C_2$, the equation for S is—

$$= l_4 (C_1 + C_2 + C_3 - x) / 30\, p.$$

***8. Ring main with n feeding points :**—We shall now consider the case of a ring main and in order to simplify the formulæ we shall suppose that it forms a circle with the power station S at its centre, and that the feeding centres are equally spaced round it. The feeders which are going radially to the respective points p_1, p_2, p_3, etc., are equidistant from one another. We shall also suppose that the load is evenly distributed, so that the points of minimum potential are midway between the feeding centres. If there are n feeders, and C is the total current output, C/n will be the current in each feeder and half of this current $(C/2\,n)$ will flow in one direction round the circle and half in the other.

Let p_1 be the drop of potential from S to any of the feeding points. Then the section of each feeder is given in square millimetres by—

$$S = (C/n)\, a/30\, p_1$$

Where a is the radius of the circle in metres.

The section S_1 of the ring main, in square millimetres, is given by—

$$S^1 = (C/2\,n)\,(2\,\pi\, a/2\,n)\ /60\,(p - p_1)$$

Hence, if V be the volume of the copper required in cubic centimetres, we have—

$$V/2 = n\,(C/n)\, a^2 / 30\, p_1 + \frac{2\,\pi\, a\,(C/2\,n)\,(2\,\pi\, a/2n)}{60\,(p - p_1)}$$

$$= C\, a^2/30\, p_1 + Ca^2\pi^2/60\, n^2\,(p - p_1)$$

By the differential calculus, V has its minimum value when—

$$p_1 = n\, p \sqrt{2} / (\pi + n \sqrt{2})$$

In this case

$$V/2 = (Ca^2/30\, p)\,(1 + \pi/n\sqrt{2})^2$$

If n were infinite, the volume V^1 of copper required would equal $2\ Ca^2/30\ p_1$ and thus

$$V/V^1 = (1+\pi/n\sqrt{2})^2$$

The following table shows how this ratio varies as n increases.

n	1	2	3	4	5	6	7	8	9	10	100
v/v^1	10·4	4·46	3·03	2·42	2·09	1·88	1·73	1·63	1·56	1·49	1·04

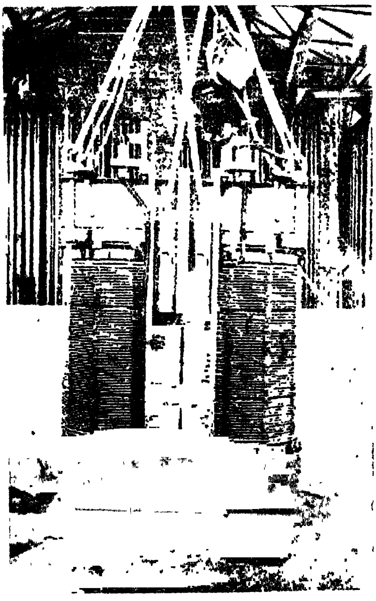
It will be seen that a substantial saving in copper is effected by increasing the number of feeders.

CHAPTER II

THE TRANSFORMER

9. Comparison of Alternator and Trans former.—In an alternator an alternating E. M. F. is produced by the cutting of a permanently established magnetic flux by wires on account of the motion of the flux relative to the wires.

In a transformer an alternating E. M. F. is produced in a stationary coil of wire (secondary) by reversals of magnetic flux through a stationary iron core. These reversals of flux are produced by alternating current supplied to the primary coil of the transformer.



Transformer Core
Fig. 2'01

10. The Chief Advantage of Alternating over Direct Current comes from the simple manner in which alternating voltage may be raised or lowered without the use of rotating machinery. Energy is transferred from the primary to the secondary of a transformer by means of the magnetic field. This is admirably done by the use of Potential Transformers.

11. A Static Transformer essentially consists of a core of laminated iron forming a closed magnetic circuit

having usually two separate and distinct coils of wire insulated from each other and wound round the magnetic circuit.

The cores are built up of thin laminæ to reduce eddy current losses. After the core and the windings are assembled, they are placed in an iron case for mechanical protection.

The two kinds of transformers, step-up and step-down, are respectively to increase and diminish the voltage of the supply.

Where the transmission of Electric Power must be made to greater distance than about five or six miles or at voltages higher than from 6,600 to 11,000 volts, the system is generally increased by the addition of step-up or central station transformers and also transformer sub-stations, where the voltage is also stepped down for distribution.

A single-phase transformer is the simplest and most efficient of all alternating current apparatus. It consists of a magnetic circuit interlinked with two electric circuits, a primary and a secondary.

12. The **windings of the transformer**, which are connected to the supply circuit, are referred to as the **Primary windings**, while those windings connected to the receiver circuit are referred to as **Secondary windings.**

Transformers designed for use on three-phase circuits, with both Primary and Secondary star connected, are usually provided with a third winding called **Tertiary winding**, which in the group is delta connected. In addition to the special office for which they are designed, they are frequently used for delivering energy to a second circuit. Transformers having more than one primary or secondary windings are referred to as *three winding, four winding, etc , transformers.*

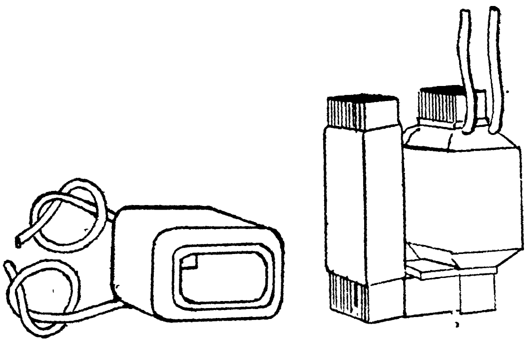
13. Type and Construction of Transformer :— There are three types of transformers, according to the disposition of the core. These are :—

(1) " Core-type " with single-magnetic circuit.
(2) " Shell-type " with double-magnetic circuit.
(3) " Berry-type " with distributed magnetic circuit.

This is rarely used.

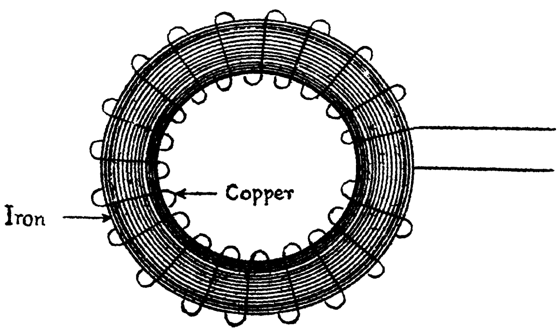
The **cruciform-type** has the two coils on the same central core, the return portion of the magnetic circuit being split in four parts.

The cruciform-type is intermediate between the core and shell types, and is the most economical of material.



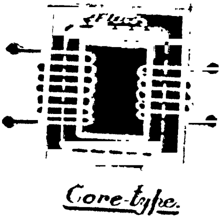
One coil of a Core-type Transformer. Core with upper yoke removed.

Fig. 2·02



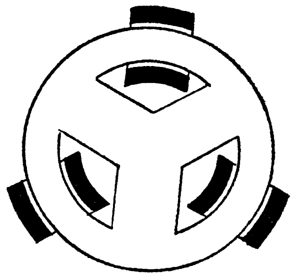
Single-phase Core-type Transformer.

Fig. 2·03



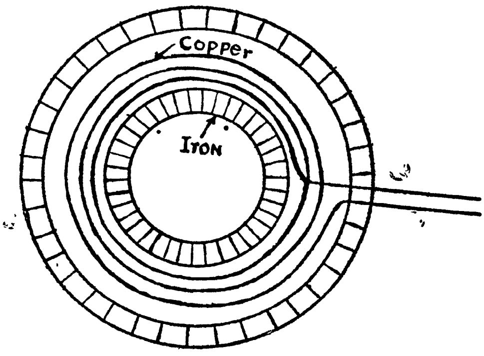
Single-phase.

Fig. 2·04



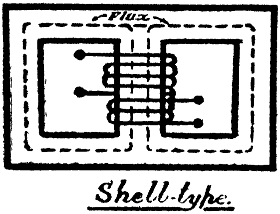
Three-phase Core-type Transformer.

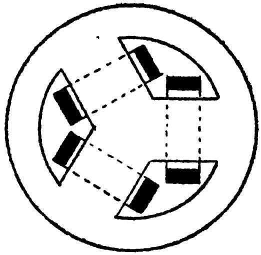
Fig. 2·05



Single-phase Shell-type Transformer.

Fig. 2·06





Single-phase.
Fig. 2·07

Three-phase Shell-type Transformer.
Fig. 2·08

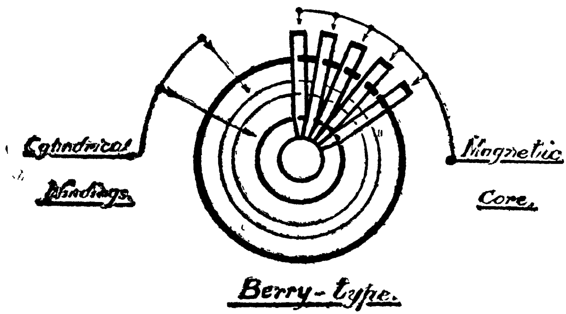


Fig. 2·09

14. Comparison of Core-Type and Shell-Type Transformers.—The core-type has relatively a lighter core of smaller sectional area but a greater length of magnetic circuit, while the copper is relatively heavier, containing more turns, although of shorter mean length of winding. The core-type is more easily wound, as cylindrical formed coils may be used, and the coils are more accessible and expose more surface to radiation. The core-type, with its relatively large winding space, is better adapted for high voltages which require many turns and large space for insulation, smaller currents, approximately below 15 amperes and. therefore, smaller wires, and higher frequencies with low magnetic flux densities.

In core-type transformers, the windings are placed around the legs of the core covering a large part of the iron and a short mean length of winding. Thus they have a smaller area of core and larger number of turns than the shell-type. The core-type is better adapted for transformers cooled directly in air than the shell-type. The core-type has long mean length or magnetic circuit and short electrical circuits and shell-type the reverse. As a general rule, the core-type construction is more economical for small high voltage transformers than the shell-type.

The shell-type, on the other hand, is particularly suited for single-phase transformers of large capacity and of moderate voltage, riquiring few turns and little insulation, large currents, and low frequency with corresponding magnetic flux, as for electric furnace work

The shell-type has interleaved primary and secondary coils on the same central core, the return portion of the magnetic circuit being split in two parts. These have short mean length of magnetic circuit and long mean lengths of windings.

The shell-type has a more robust construction, and greater facility for bracing the coils against mechanical damage which may result from short circuit

There is no tendency towards shrinkage of the insulation between the coils, as the weight of the copper does not tear directly the insulation.

The manufacturers generally adopt the core-type for transformers of small capacity and high voltage, and the shell-type for large transformers, even up to 150,000 volts. Hence, greater ease of repair in case of break-down.

15. Transients and Harmonics in Transformers :—When the magnetising circuit of a transformer is closed or opened, there are abnormal conditions of pressure or current which exist temporarily and are called **transients.**

Harmonics continue *so long as the wave-forms remain unaltered* They are oscillations of higher

frequency than the fundamental sine wave on which they are super-imposed. They result in or are the consequence of distorted wave-forms.

The current surge depends upon : (1) the point in the voltage wave at which the connection is completed ; (2) upon the magnetic state of the transformer core immediately before the circuit is closed. By switching in through a resistance which is short circuited after the current surge has subsided. The amplitude of the latter can be much reduced.

Effect of Harmonics:—Although the high initial current due to harmonics is of short duration, it may blow the fuse or cause the relays to operate and the windings are subjected to severe mechanical stresses. The saturation of the iron at the moment after closing the circuit may, under unfavourable conditions, distort the current waves, and introduce third harmonics. The high instantaneous values reached during the peak wave impose correspondingly high mechanical stresses on the windings of the transformer, under operating conditions. The harmonic components of the magnetising current may be important when transformers feed into transmission lines which are closely paralleled by telephone circuits.

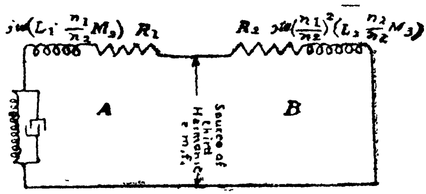
Such currents and voltages may, by electromagnetic and electrostatic induction, respectively, cause interference in adjacent telephone or relay circuits and dangerously high voltages in neighbouring conductors. Third harmonic voltages generally give more trouble than third harmonic currents.

The relative value of the harmonic components of the magnetising current at no-load will depend upon the induction of the magnetic circuit.

In a symmetrical three-phase star connected winding, with isolated neutral, there is no third harmonic current. If the neutral point is connected to a fourth conductor, then the third harmonic currents can flow in the three-phase winding. In delta connection, there can be no third harmonic in the voltage between the *lines* in such a system and no third harmonic current in the *lines*, but

A. This circuit represents virtual impredance of grounded winding with admittance lines to ground.

B. This circuit represents the virtual impredance of delta connected tertiary.



Showing equivalent circuit illustrating source and flow of third harmonic current.

Fig. 2·10

there may be a third harmonic current in the delta connected *windings*. It may cause a considerable increase in the iron losses and in the heating due to the loss and it may cause resonance at the triple frequency.

Effects of harmonics are most important where the secondary is connected to long lines. Practically, a by-pass is provided in the circuit for the flow of these harmonic currents, so that they may not make themselves objectionable by causing noise in neighbouring telephone circuits. In a transformer the permeability of the iron is not the same at all flux densities, hence third harmonics of current or voltage are produced with the transformers in addition to what may exist in the supply to the transformers.

Where the connections of the transformer winding permit the circulation of the third harmonic currents, the tendency is for such currents to flow, and for the flux and the E. M. F. waves to be sinusoidal, but if the third harmonic currents cannot circulate, the tendency is for third harmonic voltages to be established.

16. Transformers may be classified as follows according to :—

I. Purpose to be served—

(*a*) Constant voltage.
(*b*) Constant current.
(*c*) Feeder, voltage regulation.

II. Nature of use—

(a) (i) Power transformers used for transmission or used as power type in substation.

(ii) Power transformer for distribution of large quantities of energy.

(b) As used at customers' end of the distribution systems.

(c) Instrument transformers, as used in the measuring instruments and relays. Used with instrument, as potential and current transformer of small capacity and light weight but having accurate ratios.

(d) Auto-transformers for general power purpose, balancing electric circuit, etc.

(e) Constant current transformers and regulators used for street lighting.

(f) Voltage regulators used for regulating the voltage of alternating current circuits.

III. Type of magnetic circuit—

(a) Shell-type, used in large, low-voltage units.

(b) Core-type, used with small high-voltage unit.

(c) Berry-type, not generally used

IV. The type of arrangement of electric circuit :—

(a) Single or three-phase small transformers are often three-phase, but large capacity is met by the three-phase connection of the single-phase transformer.

(b) Connection of three-phase winding Δ to Δ, Δ to Y, Y to Y, open Δ.

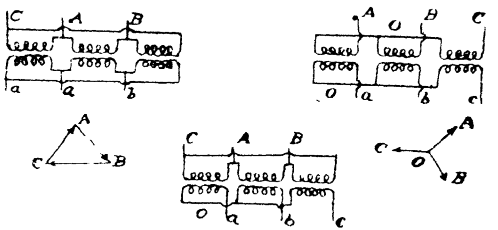


Fig 2·11

V. Method of cooling :—

(*a*) Air insulated.

(*b*) Oil insulated. Oil cooled by direct radiation or by heat transfer to separate water cooling system.

Note :—

(1) Tripping transformers primarily used with relays and trip coils.

(2) Instrument transformers used with instruments.

(3) Dry types are used up to about 23,000 volts and oil insulated above that

17. Choice of types of transformers :—Consists of the following chief points for consideration :—

(1) Type of cooling.

(2) Multiphase transformer or groups of single-phase units.

(3) Core-type or shell-type units.

Most power transformers are now of the core-type designed with circular coils, which makes it much easier to insulate the coils from each other, and especially the high-tension from low-tension In the shell-type design it is quite difficult to brace the coil against mechanical forces. The forces in the individual coils tend to cause the rectangular coils assume a circular shape, while the forces between the coils tend to cause the turns to slip by each other and spacers are modified to prevent this, the oil circulation is impeded and the heat blanketed. In circular coil type, on the other hand, the force in the individual coils which are radial does not tend to change the form of the coil which already is circular. Bracing against forces between coils is done by radial spacers, and steel plates or rings traced against the core itself, take the vertical thrust of the coil stuck. There is no impedance to air circulations nor blanketing of heat.

18. Constant Potential Transformer.—A rectangular laminated iron core C contains around its two limbs, two coils consisting of n_1 and n_2 turns of

wire. Apply an E. M. F. e_1 to the coil n_1. Suppose there is an harmonic varying flux ϕ in the laminated iron core produced by an alternate current i_1 which is due to the application of the E. M. F. e_1.

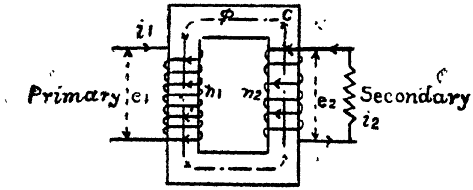


Fig. 2·12

This flux induces a certain E. M. F. in each turn of the primary and the secondary, and this E. M. F. will be the same per turn in each, provided there is no magnetic leakage. The total E. M. F. induced in either of the coils will be the E. M. F. per turn multiplied by the number of turns in the coil. Thus the E. M. Fs. e_{1b} and e_2 induced in the primary and the secondary are proportional to the number of turns n_1 and n_2 in the respective windings. Further, the induced E. M. Fs. will be in the same direction around the core.

Now e_{1b} is the back E. M. F. of the primary. By Lenz's Law it opposes the change of the flux which produces it and ultimately opposes e_1 which causes the change of flux. Also $e_{1b} = e_1$.—the E. M. F. required to send the current i_1 through the primary coil. This last E. M. F. is, however, very small in modern transformers and seldom exceeds 1 per cent. of e_1 even at full-load. That is, e_{1b} is practically equal to e_1,

$$\therefore\ e_1/e_2 = n_1/n_2 = T,$$

and is called the RATIO OF TRANSFORMATION.

The core loss which occurs while operating in open circuit is due to (*a*) eddy currents, and (*b*) hysteresis.

Again the E. M. F e_2 sends a current i_2 through the coil n_2 so as to oppose the change of flux ϕ which produces it and hence it opposes the change i_1. The magnetising effect of i_1 = demagnetising effect of i_2 + the amount necessary to produce the flux ϕ in the magnetic circuit.

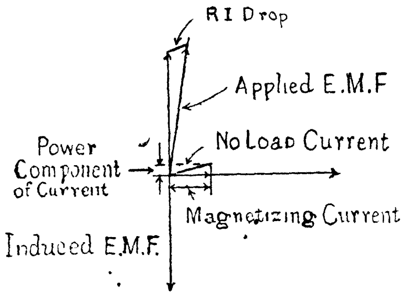


Fig. 2'13

Decrease the impedance of the secondary circuit the current i_2 will increase and the flux ϕ will be reduced. But as the flux ϕ is reduced, the back E. M. F. e_{1b} will decrease and thus a larger primary current i_1 will flow in the primary windings, so that THE CURRENT ALWAYS ADJUSTS ITSELF TO SUIT THE REQUIREMENTS OF THE SECONDARY CIRCUIT, and the automatic action of the transformer is thus seen to be due to the balanced magnetising action of the primary and secondary currents.

The primary resistance, however, is so small that e_{1b} and ϕ do not drop more than about 1 per cent. between no-load and full-load, so we may consider that ϕ is constant at all loads and thus the resultant of $n_1 i_1$ and $n_2 i_2$. the primary and secondary ampere turns, must always be equal to some quantity $n_1 i_0$ which produces the constant flux ϕ.

If the secondary circuit is opened and no current is taken from it, the current i_0 which will flow in the primary when it is connected across the mains will be very small compared with the full-load current of the

transformer because few ampere turns are required to magnetise the closed magnetic circuit having a low magnetic reluctance. This current i_0 is called the MAGNETISING CURRENT.

If i_0 be neglected,

$$n_1 i_1 = n_2 i_2$$

or $n_1/n_2 = i_2/i_1 = e_1/e_2$.

and $e_1 i_1 = e_2 i_2$.

If the loss is neglected according to the conservation of energy,

$$e_1 i_1 \cos a_1 = e_2 i_2 \cos a_2$$

and $e_1 i_1 = e_2 i_2$.

$$\therefore \cos a_1 = \cos a_2,$$

so that, neglecting the magnetising current and the losses, THE POWER FACTOR OF THE PRIMARY IS THE SAME AS THAT OF THE SECONDARY.

19. Vector Diagram for a Transformer.—

(a) No-load Conditions.—For a transformer which has a negligible no-load loss the start is made with the magnetising current The magnetism is assumed proportional at each instant to the magnetising current.

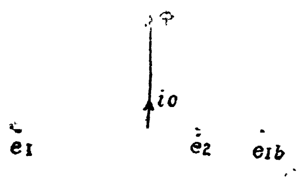
Now $\phi = \phi_{max} \sin \omega t$ where ϕ = The magnetic flux threading both the coils

$$-e = N\, d\phi/dt = \phi_{max} \times N \times \omega \cos \omega t$$

which has a maximum value $= N\phi_{max}\, \omega = 2\pi f N\phi_{max}$.

$\therefore$ the induced E. M. F. is 90° behind the flux and so 90° behind the magnetising current.

$\therefore$ The E.M.F. which must be applied to overcome this induced E.M.F. will be represented by an equal and opposite vector.



NO LOAD
Vector Diagram
Fig. 2·14

ϕ is the magnetic flux threading both coils.

i_0 is the magnetising current which produces ϕ.

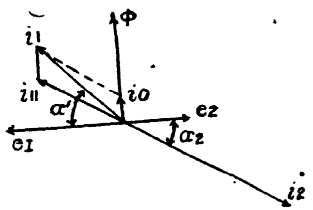
e_2 and e_{1b} are the E. M. Fs. generated in the coil n_2 and n_1, respectively, and lag the flux which produces them by 90° degrees.

e_1, the applied primary E. M. F., is equal and opposite to e_{1b}.

The current and the applied E. M. F. are at right angles and so the power is zero. But there is a core loss in the transformer ; to supply this loss there is a component of the current in phase with the applied E. M. F. This component will be represented by a vertical line. The total current will be the resultant of these two currents and is called the NO-LOAD CURRENT OR THE LEAKAGE CURRENT.

A small E. M. F. will be required to overcome the resistance of the primary coil. The drop due to this is entirely negligible It may, however, be represented by a short vector drawn parallel to the vector representing the current.

(b) Full-load Conditions.—Close the secondary circuit and let its resistance and reactance be such that i_2 lags e_2 by a_2 degrees, then the voltage and current phase relations are as shown in Fig. 2·15.



Full-load
Vector Diagram
for a Transformer

Fig. 2·15

The flux ϕ through the core threading both the coils remains constant, for it depends upon the induced E. M. F. in the primary which is always nearly equal to the applied E. M. F. The core loss is constant irrespective of the load. Hence, the no-load current i_0 is also constant and ϕ has practically the same value at full-load as at no-load.

i_0 is the component of the primary current required to produce the flux ϕ.

e_1 is the applied primary E. M. F.

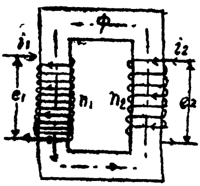
e_2 is the secondary generated E. M. F.

i_2 is the secondary current, whose value and whose phase angle α_2 depends on the constants of the connected circuit.

i_{11} is the component of the primary current required to neutralise the demagnetising effect of the current i_2 ; $n_1 i_{11} = n_2 i_2$.

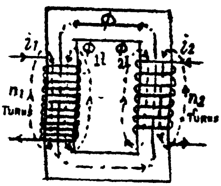
i_1 is the primary current and is the resultant of i_0 and i_{11}.

If the current i_0 is small, then $\alpha_1 = \alpha_2$ and $n_1 i_1 = n_2 i_2$.



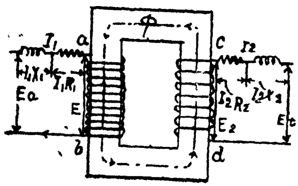
Ideal Transformer

Fig. 2·16



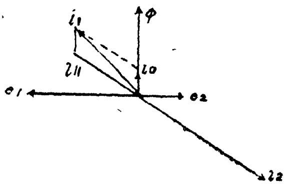
Actual flux distribution in a Transformer.

Fig. 2·17



Transformer showing the resistances and reactances diagrammatically.

Fig. 2·18



Vector diagram of an Ideal Transformer.

Fig. 2·19

20. Reactance of a Transformer.—The percentage of the total flux that links with the primary, but does not link with the secondary winding, *plus* that which links with the secondary, but not with the primary, is the per cent. reactance of a transformer.

Reactance of a transformer affects its regulation, parallel operation, mechanical stresses and eddy-current losses. A low reactance transformer has naturally a better regulation than one of high reactance, especially for highly inductive loads ; and in order to obtain a good voltage regulation it was formerly the custom to design transformers with a reactance as low as $1\frac{1}{2}$ to 2 per cent. Such a *low reactance* is, however, often *detrimental to the safe operation* of a transformer from the mechanical point of view. If a short circuit should occur at the secondary terminals of a transformer, and the power supply at the primary is sufficient to maintain the primary terminal voltage, as may be the case in very large generating systems, the primary and secondary currents of the transformer are limited by the impedance only, and, with the exception of very low reactrance transformers, it is essentially the reactance which determines the total impedance and thus the short-circuit current.

As the primary and secondary currents are opposite in phase, they repel each other, the force being approximately proportional to the square of the current. It, therefore, follows that the repulsion, which is small at full load, may reach enormous values under short-circuit conditions, if the transformer reactance is low. For example, in a transformer having a 2 per cent. reactance the short-circuit current will be 50 times normal and the mechanical stresses will increase as the square of this, or 2,500 times, amounting to many hundred tons. This clearly illustrates the necessity of a very rigid construction and also the advisability of reducing the short-circuit current to a safe value. This may be done by increasing the transformer reactance, and modern practice tends toward the use of considerably higher internal reactances than were formerly used. With modern

designs, reactances generally run from 6 to 10 per cent. and may even be higher for large high voltage units.

21. Leakage Reactance.—When a transformer is under load, the greater part of the magnetic flux passes through both the primary and secondary coils, but some flux will surround one of the coils without passing through the other. The actual flux distribution in a transformer is shown in Fig. 2·17. The ampere-turns $n_1 i_1$ produce a flux ϕ_{11}, called the primary leakage flux, which is proportional to i_1 and which threads the coil n_1, but does not thread n_2.

The ampere-turns, $n_1 i_1$ and $n_2\ i_2$ acting together produce a magnetic flux ϕ, which threads both coils n_1 and n_2 and which is practically constant in magnitude.

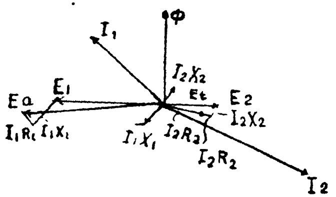
Now a coil in which a current I produces a flux ϕ, which is proportional to the current, has self-induction, and the voltage to send an alternating current I through such a coil $= IX$, where X is the reactance of the coil; the current lags this voltage by 90° degrees.

The flux ϕ_{11}, in Fig. 2·17, is proportional to the current i_1 and its effect is the same as if the coil n_1 has a reactance X_1 so that, instead of considering the effect of the flux ϕ_{11}, the effect of the equivalent reactance X_1 may be considered. In the same way the leakage flux ϕ_{21} may be represented by an equivalent reactance X_2. Fig. 2·18 shows the diagram of an actual transformer in which the leakage fluxes ϕ_{11} and ϕ_{21} are replaced by the equivalent reactances X_1 and X_2, which, along with the resistances R_1 and R_2 of the coils, are placed for convenience outside of the actual winding.

Between the terminals *ab* and *cd*, the transformer diagram in Fig. 2·18 is the same as the ideal diagram in Fig. 2·16. The vector diagram for this ideal transformer is shown in Fig. 2·19, which is the same as Fig. 2·15.

The actual terminal voltage E_t is obtained by subtracting from E_2 the vectors I_2R_2 and I_2X_2, the voltages to overcome the secondary resistance and reactance, respectively, where I_2R_2 is in phase with I_2 and I_2 lags I_2X_2 by 90° degrees.

The applied primary voltage E_a is obtained by adding to E_1 the vectors I_1R_1 and I_1X_1, the primary resistance and reactance drops.



Vector diagram of an actual transformer.
Fig 2 20

In Fig. 2·20 the ratio E_t/E_a is less than E_2/E_1 and so less than n_2/n_1, so that the transformation ratio decreases as the load increases, or the secondary voltage drops with increase of load; this drop, however, is small, being less than 2 per cent. for a 5 K.V.A transformer at 100 per cent. power factor, while for leading currents in the secondary circuit the secondary voltage may rise with increase of load just as in the case of the alternator.

22. Exciting Current.—The lag of the exciting current behind the primary impressed E M. F. in commercial transformers, is less than 90° owing to the iron losses. The exciting current has two components, one in phase with the primary E. M. F., and the other at right angles to it. The former is that current necessary to overcome the core losses, and is called the power component of the exciting current. It is expressed as—

$$I_{e+h} = \frac{P_e + P_h}{E_p}$$

where, P_e=loss of power in watts owing to eddy current,
P_h=loss due to hysteresis.

The other component of the exciting current is the magnetizing current $I\phi$ of a transformer, it is that current which sets up the magnetic flux in the core.

$$\phi = H/R = \frac{4\pi n_1 I\phi}{10R}$$

where, n_1 = total number of turns in the primary,

$$\text{whence, } I\phi = \frac{10\,R\,\phi}{4\,\pi\,n_1} = 10\,R\,\phi_m/\sqrt{2} \times 4\,\pi\,n_1,$$

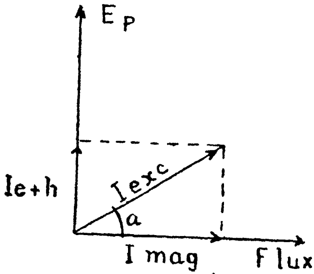


Fig. 2·21

The phase relations of the power and wattless components of the exciting current are shown in Fig. 2·21. The angle between I_{exc} and $I\phi$ is called the ANGLE OF HYSTERETIC ADVANCE and is denoted by a.

This angle is determined from the relation—

$$a = tan^{-1}\ I_{e+h}/I\,\phi.$$

The exciting current is—

$$I_{exc} = \sqrt{I\phi^2 + I_{e+h}^2}$$

and lags behind the primary impressed E.M.F. by an angle $90° - a$.

The magnitude and position of the exciting current of a transformer can be determined experimentally by the use of a wattmeter, a voltmeter, and an ammeter connected in the primary circuit, the secondary being open-circuited. The ammeter reading gives the value of I_{exc}, and its position is given by the equation—

$$a = sin^{-1}\ P/E\ I_{exc},$$

P being the wattmeter reading *minus* the copper loss due to the exciting current in the primary winding.

23. The relative magnitude and phases of the primary impressed E. M. F e_1, the primary current i_1, the secondary terminal E. M. F. e_2 and the current in the secondary winding i_2 may be expressed by the differential equations—

$$\left.\begin{aligned} R_1 i_1 + \frac{d(L_1 i_1)}{dt} + \frac{d}{dt}(M_2\, i_2) &= e_1 \\ R_2\, i_2 + \frac{d}{dt}(L_2\, i_2) + \frac{d}{dt}(M_1 i_1) &= e_2 \end{aligned}\right\} \quad \dots \quad (1)$$

If the secondary is open-circuited the current i_2 is zero, the primary current becomes the magnetising current (i_m) and equations (1) reduce to—

$$R_1\, i_m + \frac{d}{dt}(L_1\, i_m) = e_1$$

$$-\frac{d}{dt}(M i_m) = e_2$$

where $(L_1\, i_m)$, and $M i_m$ are numbers of inter-linkages of tubes of induction with the primary and secondary windings, respectively.

Note that the secondaries of power transformers should never be short-circuited except in the case of furnace transformers, whereas it is dangerous to open-circuit the secondary of an instrument transformer.

Example 1. A transformer working on 3,300 volts, 50 cycles, has 400 primary turns. The core has a mean magnetic path of 100 cm. and cross-section 1,000 sq. cm., the iron having a permeability of 1,800 The iron loss is 400 watts Calculate the primary no-load current.

Solution :—

$$\phi = \frac{4\pi\ N_1\, I}{10} \times \mu\, \frac{A}{l}$$

$$E_1 = 2\ \pi\ f\ \phi \times 10^{-8} \times N_1$$

$\therefore$ The magnetising current $I = \dfrac{E_1 l \times 10^9}{8\pi^2\, N_1^2\, A\, \mu\, f}$

$$= \frac{3{,}300 \times 100 \times 10^9}{8 \times 3\ 14^2 \times 400^2 \times 1{,}000 \times 1{,}800 \times 50}$$

$= 0{\cdot}29$ amp.

The working component—

$$I_w = \frac{\text{iron loss}}{\text{primary volts}}$$
$$= 400/3,300 = 0{\cdot}12 \text{ amp.}$$

Hence no-load current—

$$I_0 = \sqrt{0{\cdot}29^2 + 0{\cdot}12^2}$$
$$= 0{\cdot}314 \text{ amp.}$$

Example 2. When a transformer is connected to a 1,100-volt, 50-cycle supply, the core loss is 1,200 watts, of which 800 are hysteresis and 400 are eddy current loss. If the applied voltage is raised to 3,300 and the frequency to 100, find the new core loss

Solution :—

The hysteresis loss W_h can be written in the form $PB_{max}^{1{\cdot}6} f$, and the eddy current loss W_e in the form $QB_{max}^2 f^2$: P and Q being constants. Now from the E. M. F. equation—

$$E = 4{\cdot}44\ B_{max}\ AN_1\ f \times 10^{-8}$$

we see that $B_{max} \propto \frac{E}{f}$.

Hence, we can write for the hysteresis and eddy current losses—

$$W_h = PE^{1{\cdot}6} f^{-0{\cdot}6}\ ; \quad W_e = QE^2$$

where the constants P and Q now have different values.

From the data given, we have—

$$800 = P \times 1,100^{1{\cdot}6} \times 50^{-0{\cdot}6}\ ;\ 400 = Q \times 1,100^2$$
$$\therefore\ P = 800 \times 1,100^{-1{\cdot}6} \times 50^{0{\cdot}6}\ ; \quad Q = 400 \times 1,100^{-2}$$

Hence, when the voltage is raised to 3,300 and frequency to 100, we have—

$$W_h = (800 \times 1,100^{-1{\cdot}6} \times 50^{0{\cdot}6}) \times 3,300^{1{\cdot}6} \times 100^{-0{\cdot}6}$$
$$= 3,100$$
$$W_e = 400 \times 1,100^{-2} \times 3,300^2 = 3,600$$

$\therefore$ Total loss under the new conditions—

$$= 3,100 + 3,600$$
$$= 6,700 \text{ watts.}$$

24. Equivalent Impedance, Resistance and Reactance of a Transformer :—If a current of definite magnitude and lag be taken from the secondary of a

transformer, a current of the same lag and T times that magnitude will flow in the primary, neglecting resistance, reactance and hysteresis. An impedance, which, placed across the primary mains, would allow an exactly similar current to flow, as this primary current is called an EQUIVALENT IMPEDANCE, and its components are called EQUIVALENT REACTANCE.

The EQUIVALENT RESISTANCE of a transformer is the resistance which, when multiplied by the square of the current in the circuit, gives the total copper loss of the transformer. Its magnitude varies with the variation of current in the primary or secondary.

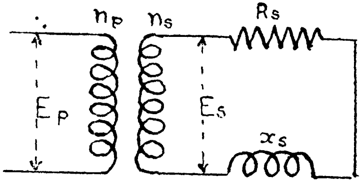


Fig. 2·22

If R = the equivalent resistance of a transformer,
R_p = the resistance of the primary winding,
R_s = the resistance of the secondary winding,
i_1 = the primary current,
i_2 = the secondary current,
P_p = copper losses in the primary,
P_s = copper losses in the secondary,
The total copper losses in the transformer—

$$= P_p + P_s$$

$$= R_p i_1^2 + R_s i_2^2.$$

But $i_1 = i_1\ n_2/n_1$ (Art. 18).

$$i_2 = i_1\ n_1/n_2$$

∴ the total copper loss as in the transformer—

$$= [R_p + R_s (n_1/n_2)^2] i_1^2$$

$$= [R_s + R_p (n_2/n_1)^2] i_2^2$$

$R = R_p + R_s (n_1/n_2)^2$, when referred to the primary circuit.

$= R_s + R_p (n_2/n_1)^2$, when referred to the secondary circuit

THE EQUIVALENT REACTANCE of a transformer is the ratio of the voltage drop due to the inductance of the windings and to leakage flux and the current flowing in the circuit. It is determined from the short-circuit test and the equivalent resistance of the windings.

$$X=\sqrt{(E/I)^2-R^2}$$

where, X=the equivalent reactance of the transformer referred to the primary or the secondary circuit as the values of E/I and R are primary or secondary circuit.

E=the value of the primary or the secondary $E.M.F.$ required to cause the current to flow in it, the primary circuit or the short-circuited windings.

I=the current flowing in the primary circuit or in the short-circuited windings.

R=the equivalent primary or secondary resistance of the windings.

If the secondary winding of the transformer has a resistance R_s and a reactance X_s and if the load has a resistance R_2 and a reactance X_2, then the current that will flow in the secondary is—

$$I_2=\frac{E_2}{\sqrt{(R_s+R_2)^2+(X_s+X_2)^2}}$$

where, E_2 is the secondary impressed pressure, when E_1 is the primary impressed $E.\ M.\ F$

The equivalent resistance$=(n_1/n_2)^2\ R_s$.

The equivalent secondary reactance$=(n_1/n_2)^2\ X_s$.

The equivalent load resistance$=(n_1/n_2)^2\ R_2$.

The equivalent load reactance$=(n_1/n_2)^2\ X_2$.

Since the resistance and reactance of the primary are small, the difference between the impressed voltage E_0 and E_1, the counter $E.\ M.\ F.$ inside the transformer, is small compared to E_0. Hence, the circuit may be simplified by transforming the magnetising current circuit to the primary terminals.

If R_t =equivalent total resistance.

X_t =equivalent total reactance of the primary and secondary windings of the load,

$$R_t = R_p + (n_1/n_2)^2\ R_s + (n_1/n_2)^2\ R_2$$
$$X_t = X_p + (n_1/n_2)^2 X_s + (n_1/n_2)^2\ X_2$$

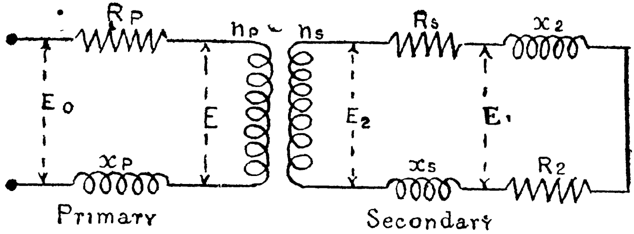


Fig. 2·23

25. The complete vector diagram of *E. M. Fs.* and currents in a transformer corresponding to the arrangement of Fig. 2·23 is represented in Fig. 2·24, where

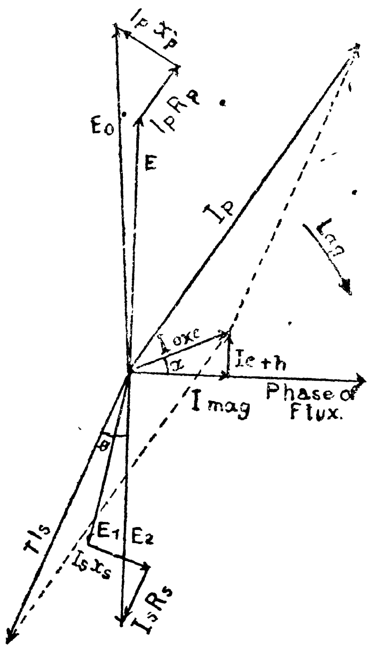


Fig. 2·24

I = the magnetising current,

E_1 = the difference of potential at the secondary terminals,

E_2 = *E. M. F.* induced in secondary winding,

E_0 = impressed primary pressure,

E = operative part of E_0,

$1/T = n_1/n_2$ = ratio of transformation,

I_p and I_s = primary and secondary currents, respectively.

For clearness one to one ratio has been taken, and the various drops are greatly exaggerated.

$$I_{e+h} = \frac{P_e + P_h}{E_p}$$

The current flowing in the secondary circuit is

$$I_s = \frac{E_2}{\sqrt{(X_s + X_2)^2 + (R_s + R_2)^2}}$$

and lags or leads the secondary induced E. M. F. by an angle ϕ whose tangent is $(X_s + X_2)/(R_s + R_2)$, the secondary induced electromotive force being 90° behind the flux. The primary current I_p is equal to the vectorial sum of T times the secondary current and the exciting current. When a small current is taken from the secondary of the transformer, the directions of I_p and I_s are considerably less than 180° apart, but when the secondary current is large, the directions of I_p and I are approximately opposite.

The secondary induced E. M. F. is not at all utilised at the terminals. There is a resistance drop of $I_s R_s$ volts which is in phase with I_s, and a reactance drop of $I_s X_s$ volts due to the leakage flux, this being at right angles to the phase of the secondary current

The result of subtracting $I_s R_s$ and $I_s X_s$ from E_2 vectorially is E_1, which is the difference of potential at the secondary terminals.

The operative part, E, of the primary impressed electromotive force, which is necessary to produce the secondary induced pressure E_2, leads the latter by 180°, and its magnitude is E_2/T. There is a primary resistance drop of $I_p R_p$ volts in phase with I_p and a reactive drop due to leakage of $I_p R_p$ volts at right angles to I_p. Therefore, the E. M. F. impressed upon the primary terminals necessary to produce E is the vectorial sum of E, $I_p R_p$ and $I_p X_p$, and is denoted by E_o

Both R_s and R_p become known quantities as soon as the size of the secondary and primary conductors is known. The values of X_s and X_p are calculated.

In the circuit in Fig. 2·25, the secondary resistances and reactances are reduced to the primary circuit, and the exciting current is considered as flowing through a separate impedance, thus eliminating all transformer action.

A transformer diagram of practical importance is dependent upon the consideration that the exciting current may be neglected when the apparatus carries a large load.

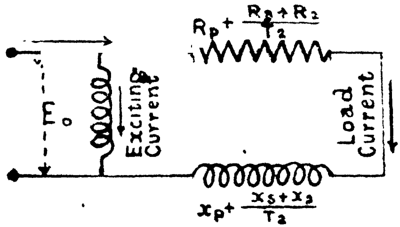


Fig. 2'25

It follows that $I_p = I_s$, and that I_p is exactly opposite I_s. The primary and secondary resistance drops, being in phase respectively with I_p and I_s, are parallel, and the latter may be reduced to the primary circuit and added algebraically to $I_p R_p$. Then the total equivalent resistance drop of the transformer is $I_p\ (R_p + R_s/T^2)$. Similarly, the total equivalent reactance drop of the transformer is $I_p\ (X_p + X_s/T^2)$ and is at right angles to I_p or I_s. The impressed primary E. M. F. E_0 is equal to the vectorial sum of E_1, $I_p\ (R_p + R_s/T^2)$, and $I_p\ (X_p + X_s/T^2)$, as shown in Fig. 2'26. Hence, the regulation is expressed by—

$$\text{Regulation} = \frac{E_0 - E_2/T}{E_2/T}$$
$$= (T\ E_0 - E_2)/E_2.$$

In practice, it will be found impossible to complete

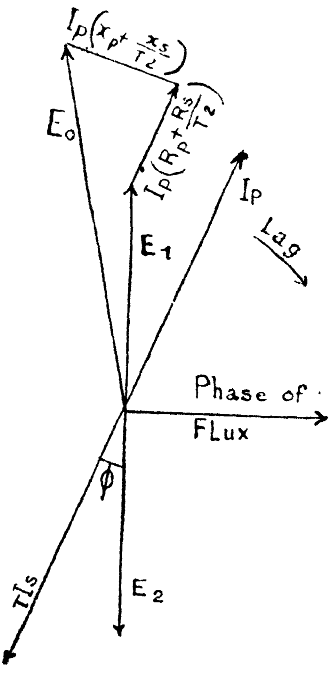


Fig. 2'26

the solution of these diagrams graphically, because of the extreme flatness of the triangles. The better way is to draw an exaggerated but clear diagram, and obtain the true value of the sides by the methods of trigonometry and geometry.

26. Circle Diagram.—The magnitude and phase of the current produced by a constant impressed primary electromotive force E_o, Fig. 2·27, depends upon the resistance and reactance of the circuit. Consider the load to be non-inductive, in which case the current supplied to it is dependent upon the load. The equivalent total resistance R_t and reactance X_t vary with the load, if the load supplied to it is dependent upon the resistance of the load as the total reactance is constant.

The impressed E. M. F. has two components—that necessary to overcome the reactive drop, due to the leakage flux in the transformer itself, and that necessary to overcome the resistance drop due to the resistance of the entire circuit if the effect of shunt exciting circuit is neglected. These are at right angles to each other and may be represented respectively by $(I_p X_p + X_s/T^2)$ and $I_p\,[R_p + (R_s + R_2)/T^2]'$ as shown in the Fig. 2·27. If the resistance of the load be altered, the current will be changed and the point P will be in a different position, since $X_p + X_s/T^2$ is constant. However, the impressed E. M. F. is always equal and opposite to the resultant of the reactance drop and the resistance drop, and to satisfy this condition of locus of the point P must be a semicircle. As I_p is proportional to the reactive drop, and since the two angles marked θ are equal, it follows that the locus of the point B is also a semicircle. The diameter of this semicircle is $E_o/(X_p + X_s/T^2)$ amperes, which is the condition corresponding to zero resistance.

Thus, the locus of the load current for various resistances, when the load is non-inductive, is a semicircle whose diameter is the ratio of the primary impressed E. M. F. to the total equivalent reactance of the transformer, and whose diameter is at right angles to E_o.

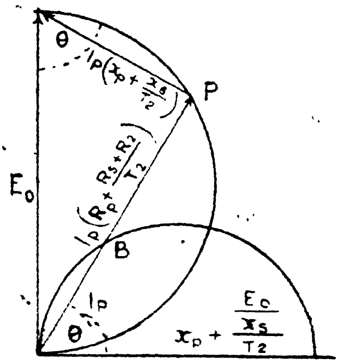


Fig. 2·27

The total current produced by E_o of Fig. 2·26, when the load is non-inductive ($X_2 = 0$), is the victorial sum of I_p and $I_{exc.}$ as shown in Fig. 2·28. The resulting primary current lags behind E by an angle ϕ, and the power factor of the complete circuit is the ratio of E_oM to AM or $\cos\ \phi$. The power supplied to the transformer is the product of I_p and E_oM. Knowing the copper and core losses, the output P may be computed, and the efficiency of the transformer determined. The regulation is then obtained as follows :—

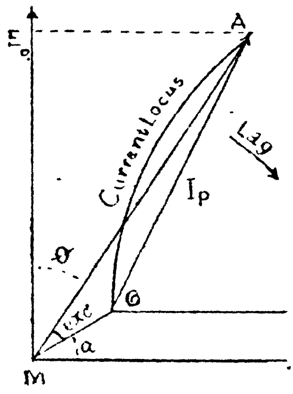


Fig 2·28

$$\text{Regulation} = \frac{TE_o - P/I_s}{P/I_s} = \frac{TE_oI_s - P}{P}$$

27. The Regulation of a Transformer.

The regulation of a transformer is defined as the rise in voltage of the secondary when the full-load is thrown off the transformer divided by the full-load voltage, the frequency and primary voltage remaining constant and the wave of impressed E.M.F. is sinusoidal. Good regulation means that the secondary voltage varies but little and is highly desirable.

It depends upon its design and upon the character of the secondary load; the less inductive the load, the better the regulation of a given transformer.

The direct method of determining regulation is to take the voltage at full-load and at no-load, and obtain the rise in the secondary voltage.

This means loading the transformer.

(*a*) On an artificial inductive load consisting of chocking coils and resistances. This is expensive.

Or, (*b*) On an artificial non-inductive load such as water resistances. This will give regulation only at unity power factor.

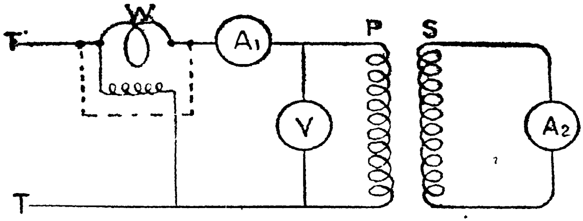
The method is unsatisfactory because of the small difference between the full-load and the no-load values, and the liability of error in measurement. Much more reliance can be placed on results calculated from separate measurements of impedance drop and resistance than on actual measurement of regulation.

The following formula is simple and practically correct.

Per cent. regulation—

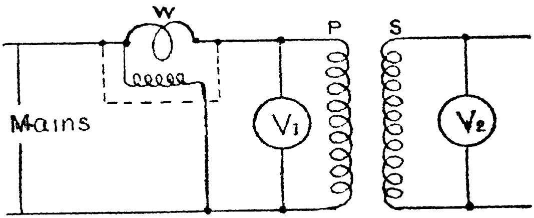
$$=pRI+q\times I+(p\times I-qRI)^2/200,$$

in which RI is the total resistance drop in the transformer due to load current expressed in per cent. of rated *voltage*; XI *is total* reactive drop due to the load current similarly expressed, p is the power factor of the *load on the* secondary$=cos\ \phi$, for a non-inductive load $p=1$ and q is the reactive factor of the load$=sin\ \phi$



Short-circuit Test.

Fig. 2·29



No-load Test.

Fig. 2·30

The regulation is generally determined with the help of values obtained from the no-load and short-circuit tests The connections are given in the Figs. 2·29 and 2·30

Compare the experimental determination of the circle diagram of induction motor.

But the nature of the load decides the regulation, and if the current is leading, the regulation may be negative. and thus the term is meaningless. unless the conditions are known.

Per cent. Regulation=

$$\left[\left\{\sqrt{(E_s \cos\phi + RI_s)^2 + (E_s \sin\phi + XI_s)^2} - E_s\right\} / E_s\right] \times 100$$

4

Where E_s = full-load rated secondary voltage.
I_s = full-load rated secondary current.
R = equivalent secondary resistance.
X = equivalent secondary reactance.
$Cos\ \phi$ = power-factor of the load circuit.

Example 3. Determine the regulation of a 20, K. V. A, 2,200 : 220 volt transformer if 110 volts must be applied to the 2,200 volt winding to cause rated current to flow in the short-circuited secondary winding.

Given—
$R_p = 1{\cdot}5$ ohms.
$R_s = 0{\cdot}015$ ohms.
$Cos\ \phi = 1.$
$E_s = 220$ volts.
$P_o = 250$ watts

$$\frac{E_1}{E_2} = \frac{n_1}{n_2} = \frac{2{,}200}{220} = \frac{110}{E_2}$$

$$\therefore \quad E_2 = \frac{220 \times 110}{2{,}200} = 11$$

Solution :—

$I_s = 20{,}000/220 = 91$ amperes, nearly.
$R = 0{\cdot}015 + 1{\cdot}5 \times (1/10^2) = 0{\cdot}03$ ohm.
$X = \sqrt{(11/91)^2 - ({\cdot}03)^2} = 0{\cdot}116.$
$RI_s = 91 \times {\cdot}03 = 2{\cdot}73$ volts.
$XI_s = 91 \times 0{\cdot}116 = 10{\cdot}6$ volts.

$$\frac{E_2}{I_2} = Z_2$$

$$X = \sqrt{Z_2^2 - R_2^2}$$

Per cent. Regulation

$$= \frac{\sqrt{(220+2{\cdot}73)^2 + (10{\cdot}6)^2} - 220}{220} \times 100$$

$$= \frac{223 - 220}{220} \times 100 = 300/220 = 1{\cdot}36 \text{ per cent.}$$

Example 4. A 10-kW, 50-cycle transformer of 10 to 1 ratio with the secondary voltage of 220 volts has the following constants :—

Primary resistance $R_p = 4$ ohm.

Primary $R_pI_p = 4 \times 4{\cdot}55 = 18{\cdot}2$ volts or % R_pI_p

$$= \frac{18{\cdot}2}{2{,}200} \times 100 = 0{\cdot}827\ \%.$$

Secondary resistance $R_s = 0{\cdot}03$ ohm.

Secondary $R_sI_s = 0{\cdot}03 \times 45{\cdot}5 = 1{\cdot}365$ volts or % $R_sI_s = 0{\cdot}62$ %.

Total RI (reduced to primary) $= 18{\cdot}2 + 10^2 \times 1{\cdot}365 = 154{\cdot}7$ volts.

Reactive drop, $XI = 3{\cdot}36$ %.

RI is determined from test and XI from calculation.

(1) Regulation on non-inductive load.

Here $\cos\theta = 1 = p$ and $\sin\theta = 0 = q$.

$$\% \text{ regulation} = 1 \times 1{\cdot}45 + 0 \times 3{\cdot}36 + \frac{(1 \times 3{\cdot}36 - 1{\cdot}45 \times 0)^2}{200}$$

$$= 1{\cdot}45 + 0{\cdot}056 = 1{\cdot}506.$$

(2) Regulation on inductive load:

Assuming the power factor of the load to be—

$0{\cdot}80 = p,\ q = \sqrt{1 - {\cdot}8^2} = 0{\cdot}6.$

$$\therefore \quad \% \text{ regulation} = 0{\cdot}8 \times 1{\cdot}45 + 0{\cdot}6 \times 3{\cdot}36 + \frac{({\cdot}8 \times 3{\cdot}36 - 1{\cdot}45 \times {\cdot}6)^2}{200}$$

$$= 1{\cdot}16 + 2{\cdot}016 + 0{\cdot}0165 = 3{\cdot}19$$

The regulation for any other power factor p may be calculated in a similar manner.

28. Graphical Method.—Let OI be the primary current vector and OE represent to scale the primary voltage on the short circuit, so that $\cos EOI = \cos\phi$, the power factor deduced from the short-circuit test.

Draw OX such that the angle $XOI = \alpha$, where $\cos\alpha$ = power factor of the secondary load.

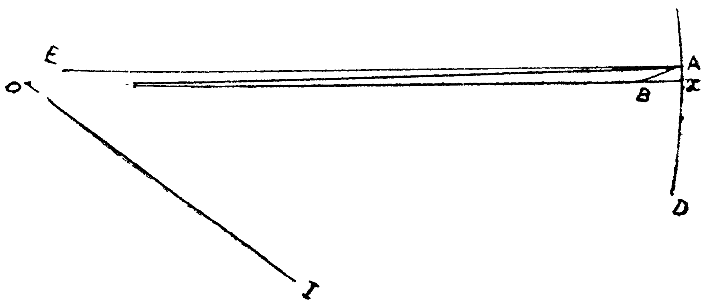


Fig. 2·31

With centre O and radius equal to the primary impressed voltage draw an arc AD.

On this arc must lie the end of the vector representing the applied voltage.

EA with A on the arc D is next drawn parallel to OX and AB parallel to EO.

If the transformation ratio be unity, OB would represent the secondary voltage on the full-load and OA the secondary voltage on no-load.

If the ratio of transformation is T, we must first ascertain by scale measurement what voltage OB represents and then divide it by the transformation ratio to get its true value.

The regulation of a polyphase transformer can be ascertained working one phase only. The power factor for a polyphase transformer is obtained from the following :—

$$\frac{\text{Watts per phase.}}{\text{Primary Phase Current} \times \text{Primary Phase Volt.}}$$

Example 5. In a 20 K. V. A. transformer on the no-load test the primary voltage was 2200, and the secondary was 550 volts. On the short-circuit test the primary volt was 144 when the secondary current was 25 amps. and the primary current being 6 amps., and the primary watts 360. Determine the regulation of the transformer and the actual secondary voltage at full-load having a power factor of ·8.

From the no-load test readings we get—

Transformation ratio $= 2200/550 = 4$.

From the short-circuit test readings we have—

Power factor on short circuit $= 360/144 \times 6 = {\cdot}417$.

$\cos^{-1} {\cdot}417 = 65^\circ - 21'$.

$\therefore$ the angle of lag of current behind voltage is $65^\circ - 21'$.

Draw OI, Fig. 2·31, to represent the primary current vector and OE to represent the primary voltage on short-circuit test, leading $65^\circ - 21'$ in front of the current. Power factor $= {\cdot}8$. ·8 is the cosine of an angle of $36^\circ - 52'$.

∴ the phase difference between the secondary current and the secondary terminal voltage=36°−52′. Draw OX making the angle IOX=36°—52′.

Then with centre O and radius (to same scale as before) equal to 2200 (the primary impressed voltage) draw an arc AD.

On this arc must lie the end of the vector representing the applied voltage.

Next, EA with A on the arc AD is drawn parallel to OX and AB is drawn parallel to OE

If the transformation rated were unity, OB would represent the secondary voltage on the full-load and OA the secondary voltage on no-load.

But here the transformation ratio is 4.

We ascertain by scale measurement that voltage OB represents 2060 and then divide it by the transformation ratio 4 and get its true value as 515.

We already know that the secondary voltage on no-load is 550.

Hence :—

$$\text{Regulation} = \left\{ (550-515)/515 \right\} \times 100$$
$$= 6{\cdot}79.$$

29. Kapp Regulation Diagram.—

The graphical method of determining the voltage drop in a transformer is shown in the Fig. 2·32. A vector OP is drawn to represent the secondary terminal voltage on loads and OX is drawn inclined at an angle ϕ to OP, where $\cos\phi$ is the power factor of the load. Then OX represents the phase of the secondary current. Draw PQ parallel to OX and equal to resistance drop referred to the secondary, namely, $R_2 I_2$; and the perpendicular QR equal to the reactance drop referred to the secondary, namely, $X_2 I_2$ Then the triangle RPQ is the drop triangle referred to the secondary, and RP is the total voltage drop. Hence, OR is the secondary no-load voltage E_2 and (OR-OP), arithmetic difference, is the secondary drop from no-load to full-load. Now, if the triangle RPQ is transferred to OED, as shown, then $EP=OR=E_2$ Hence, for a given secondary current, the locus

of R is a circle with centre O and radius E_2, while the locus of P is a circle with centre E and the same radius. In order to find the voltage drop on full load at any power factor *cos* ϕ, a radius OBS is drawn inclined at an angle ϕ to OX. If the impedance triangle is drawn in the position ABC, then $OA = OS$, the no-load secondary voltage, and OB, the voltage on load. Hence, the length BS is the voltage drop. It is obvious that the traingle ABC

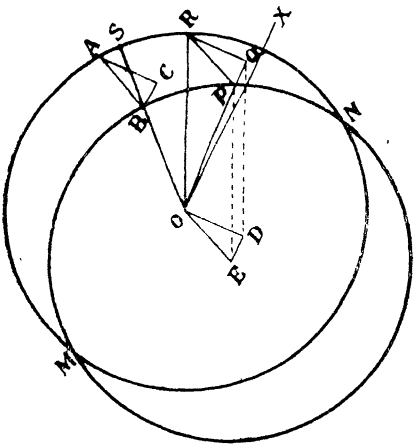


Fig. 2·32

need not be drawn, but simply the radius OBC. It will be seen that for all phase angles ϕ included between $\angle XON$ (which is leading) and and $\angle$ MOX (which is lagging), there is a drop of volts on load. For phase angles equal to either of these two limits the voltage on load is equal to that on no-load. For phase angles between $\angle MOX$ and $\angle XON$ (reckoning in a counter-clockwise direction) there is actually a rise of voltage on load.

The Kapp diagram affords a very convenient means of determining the variation of regulation with power factor, but it has the *disadvantage* that since the lengths of the sides of the impedance triangle are small compared with radius of the circles, the diagram has to be drawn to a very large scale if accurate result are to be obtained.

30. The Efficiency of Transformers.

$$\text{The Efficiency of Transformers} = \text{Output/Input}$$
$$= \text{Output/(Output + Losses)}$$

As in the case of alternators the losses are :—

(1) Iron losses.—The hysteresis and eddy current losses in the core.

(2) Copper losses.—These are $I_p^2 R_p$ and $I_s^2 R_s$ watts, respectively, for the primary and secondary windings. Note that there is no power loss due to the primary and secondary inductances.

The efficiency should be improved with non-inductive load and at rated frequency, except, where expressly specified otherwise. The efficiency varies from 99 per cent. in large transformers to 95 per cent. in smaller ones.

The transformer efficiency is usually calculated for unity power factor when $\cos\phi$, the power factor of the load circuit, is unity.

Let P_o=the no-load input (iron losses).

R =the equivalent primary resistance of the secondary windings.

η= efficiency,

$$\text{Per cent. efficiency}=\eta=\frac{E_s I_s \cos\phi}{E_s I_s \cos\phi+P_o+R I_s^2}$$

$$=\frac{E_s I_s \cos\phi}{E_s I_s \cos\phi+R I_s^2+P_e+P_h}$$

31. The efficiency of a transformer is maximum when the iron loss is equal to the copper loss.

The efficiency is maximum when $d\eta/dI_s=$

$$(E_s I_s \cos\phi+R I_s^2+P_e+P_h)\,E_s\cos\phi-E_s I_s\cos\phi\,(E_s\cos\phi+2RI_s)=0$$

$Or,\ P_e+P_h=R I_s^2$.

That is, the iron loss is equal to copper loss.

Example 6. Find the full-load efficiency of a 20 K. V. A 2.200 : 220 volt transformer if the no-load input to it is 250 watts, R_p=1 ohm, R_s=0·02 ohms.

E_s=220 volts. I_s=2,200/220.

$\therefore I_s = 91$ amperes.

$P_o = 250$ watts. $R_e = 0{\cdot}02 + 1/100 = 0{\cdot}03$

$\therefore R_e = 0{\cdot}03$ ohm.

$R_e I_s^2 = 248{\cdot}5$ watts approximately.

$Cos\ \phi = 1$

Per cent. efficiency $= (20{,}000 \times 100)/(20{,}000 + 250 + 248{\cdot}5)$
$= 20{,}00{,}000/20498{\cdot}5 = 97{\cdot}5$

32. The all-day efficiency of a transformer is the ratio between the readings of a watt-hour meter connected on the secondary and a similar meter on the primary or the total output during twenty-four hours to the total input during the same period.

$$\text{All-day efficiency} = \frac{\text{Output during 24 hours}}{\text{Input during 24 hours}} = \frac{\text{Output during 24 hours}}{\text{Output during 24 hours} + \text{losses}}$$

If h = hours per day of secondary load.

h_1 = hours per day that transformer is on line.

P_s = secondary output in watts.

P_o = core loss in watts = input for no-load on secondary approximately.

$$\text{All-day efficiency} = \frac{100 \times P_s \times h}{P_s h + h_1 P_o + h R_s I_s^2} \text{ per cent.}$$

Example 7. Find the all-day efficiency of the transformer (as in Example 6) when operated at full-load for 10 hours.

Solution :—

$$\text{Per cent. efficiency} = \frac{20{,}000 \times 10 \times 100}{20{,}000 \times 10 + 250 \times 24 + 248{\cdot}5 \times 10}$$
$$= 95{\cdot}9$$

33. The power factor of a transformer on non-inductive external secondary circuit is a maximum when the copper losses and iron losses are equal.

For, if W_h = iron losses in watts, we have the total power delivered to the transformer at

a supply voltage of E_1, the line current being I and the power factor $\cos\phi$.

$$E_1 \; I\cos\phi = e_1 \; I + I^2 \; r_1 + I_2^2 \; r_2 + W_h$$

But, working at the same current density in both circuits

$$I^2 \; r_1 = I_2^2 \; r_2$$

therefore, $E_1 \; I\cos\phi = e_1 \; I + 2\,I^2 \; r_1 + W_h$

Hence, $\cos\phi = (e_1 \; I + 2\,I^2 \; r_1 + W_h)/E_1 \; I$

$$= e_1/E_1 + 2r_1/E_1 \; I + (W_h/E_1) \; 1/I = y \text{ (say)}$$

$$\therefore \; dy/dI = 2r_1/E_1 + (W_h/E_1) \; (-1/I^2) = 0$$

which is the condition for $\cos\phi$ to be maximum,

i.e., $2r_1 \; I^2 = W_h$

which proves the statement.

The losses in a transformer ultimately appear as heat in the windings and the core. The heat must be dissipated, otherwise too high a temperature will seriously damage the fibrous and insulating materials which disintegrate and lose their mechanical and dielectric strength and the iron deteriorates in its magnetic qualities and the core loss becomes greater for a given density.

34. Transformer Equations—

For any transformer or reactive coil

Let E = effective value of the induced E. M. F.

ϕ_m = total maximum flux produced in the iron core.

B = lines of force per square inch.

f = the frequency in cycles per second.

A = cross-section of the iron.

n = total number of turns of wire in series in the coil.

The average rate of change of flux is—

$$\phi_m/1/4f = 4\phi_m f$$

$$F_{av.} = 4\phi_m fn \; 10^{-8}$$

$$E = 4{\cdot}44 \; \phi fn \; 10^{-8}$$

The equation is based upon the assumption of sin wave of electromotive force when the form factor is 1·11.

If the volt, frequency and turns are known.—

$$\phi = \frac{E \times 10^8}{4{\cdot}44\, f\, n}$$

$$\text{But, } \phi = B\,A$$

$$\therefore\ A = \frac{E \times 10^8}{4{\cdot}44 \times f \times n \times B}$$

which gives at once the cross section of the iron necessary for the magnetic circuit after we have decided the total primary turns and the density at which it is designed to work the iron. Again if volts, frequency, cross-section of core and density are known, we have—

$$n = (E \times 10^8)/(4{\cdot}44 \times f \times B \times A).$$

Example 8. Specify a transformer for a two-phase motor which delivers 100 h. p. at 440 volts with an efficiency of 92 per cent. and a power factor of 88 per cent. the line voltage being 2200.

Solution :—

Motor Output = 100 h. p.
= 100 × 0·746 kW. = 74·6 kW.
Motor Input = 74·6/0·92 = 81·09 kW.
= 81·09/0·88 = 92·1 K.V.A.

Therefore two transformers are required each of 46 K. V. A. output.

The secondary current = 46000/440 = 104·5 amps.

The primary current, neglecting losses in the transformer = 46,000/2,200 = 21 amperes nearly.

Example 9. The net sectional area of the core of a transformer is 20 square inches and the maximum value at the alternating flux density due to the primary current is 50,000 lines per square inch. Determine the number of turns in the secondary winding, so that it may generate an E. M. F. of 250 volts on open circuit The frequency is 550 cycles per second.

Solution :—

Total flux = 20 × 50,000 = 10,00,000. $E = 250$.

$T = (10^8 \times 250)/(4{\cdot}44 \times 50 \times 50{,}000 \times 20) = 113$ turns.

35. Banking of Transformers.—Two service mains may be supplied with current by two or more transformers with their primaries connected in parallel between the supply mains and with their secondaries properly connected in parallel to the service mains.

When transformers are banked or put in parallel, their primaries are connected in parallel to the same line and their secondaries are connected in parallel to the same busbars.

Advantage :—Lower total Kilovolt ampere capacity is required for the same load and better all-day efficiency is secured than when transformers are operated independently.

Disadvantage :—An accident to one transformer will generally interrupt the service from the others in the bank.

Limit :—The cost of low tension transmission system and the characteristics of the connected apparatus limit the extent to which this banking can be successfully and economically carried.

Perfect operation of two or more transformers in parallel means that each of the separate units contributes to the total load an amount of power proportional to its rated output, and that the numerical sum of the currents in the separate units is equal to the line (total) current.

Stated briefly, the **characteristics and adjustments necessary** to make transformers operate properly in parallel are as follows :—

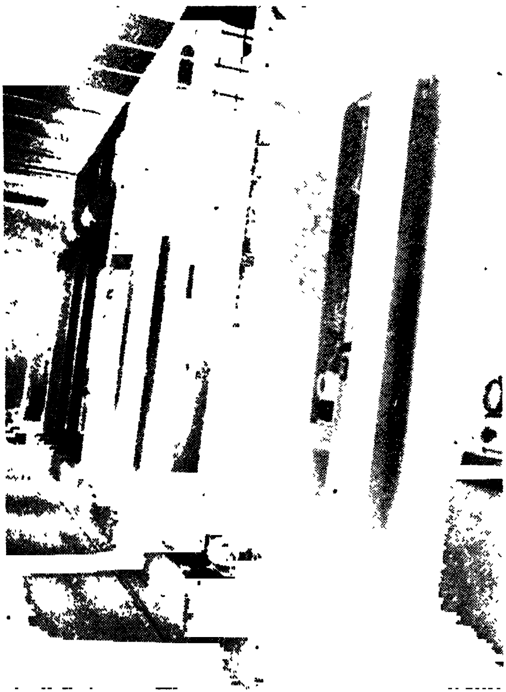
(1) The ratio of primary turns to secondary must be the same in all the units.

(2) The ratio of primary to secondary voltage should be the same for all transformers in parallel.

(3) Voltage drop from no-load to full-load must be the same, both in magnitude and phase, for all the unit.

(4) Secondary terminals of similar polarity should be connected together or to the same low-tension mains.

(5) The percentage of impedance should be approximately the same for all transformers in the same tank.



Bank of Transformers 220-78,000 volts
(Shivasamudram.)
Fig. 2·33

(6) The ratio of resistance to reactance, or of resistance or reactance to impedance, should be the same for all of the transformers.

Consider the effects of violating each one of these requirements separately, while the others are satisfied. For simplicity take only two transformers

(1) **Transformation ratios unequal** :—The effect will be that there will be a difference having at all loads in the secondary voltages, and the transformer having the highest voltage will carry the largest load.

(2) **Voltage ratio unequal** :—If the voltage ratios are not equal, the transformers having the higher secondary induced voltage will force current through the other against its induced E. M. F. in such amount as will consume the difference of induced voltage in overcoming the total impedance of the local circuit formed by the two secondaries. This current will flow even when no external load is connected, and will result in increased losses and reduced capacity to carry useful load.

To determine this current, assume that E_1 and Z_1 are the voltage and impedance in low-voltage terms of one transformer and E_2 and Z_2 are corresponding terms of the second transformer, connected in parallel with the other. The circulating current would then be

$$i = \frac{E_1 - E_2}{Z_1 + Z_2}$$

where Z_1 and Z_2 are expressed in ohms, or expressed in percentage of normal current by the following formula :—

$$\text{Per cent. } I = \frac{\text{per cent. voltage difference}}{\text{Sum of per cent. impedance}} \times 100.$$

For example, suppose that the voltage ratios of two transformers are such as to cause a voltage difference of 2 per cent. If each transformer, furthermore, has a 2 per cent. impedance, the circulating current is equal to—

$$\text{Per cent. } I = \frac{2}{2+2} \times 100 = 50 \text{ per cent.},$$

which means that a current equal to 50 per cent. of normal circulates between the transformers in both high- and low-voltage windings. It adds to the load current in the transformer having the higher induced voltage and subtracts in the other, causing the former to carry the greater load

The impedance Z_1 can be found for the first transformer by impressing a voltage on the low-voltage winding with the high-voltage winding short-circuited.

The current is then read, and if I is the current and E the voltage, then $Z_1 = \frac{E}{I}$. In the same manner Z_2 is determined.

With three-phase delta-delta connected transformers, different voltage ratios will cause unbalanced voltages and set up a circulating current within the delta in both the high and low-voltage windings. Unbalanced voltages outside the delta can, however, not produce any circulating currents within the delta, and unbalanced voltages applied to a delta-connected transformer bank cannot be equalised on the low-voltage side by the introduction of additional voltage in the delta.

As with single-phase transformers the value of the circulating current is obtained by dividing the voltage difference by the total impedance of the transformer bank. For example, if three transformers having impedance of 4 per cent. are connected delta-delta, and one has ratio 1 per cent. greater than the other two, the resulting circulating current will be—

$$\text{Per cent. } I = \frac{1}{3 \times 4} \times 100 = 8{\cdot}33 \text{ per cent.}$$

When the load is taken from such a bank, the load currents and circulating currents are superimposed, and the transformer having the highest secondary voltage will carry the greatest load, as before.

With delta-Y connected transformers a slight difference in the ratios has a very small effect compared with a delta-delta connected bank. This is due to the shifting of the neutral point, causing an equalisation of the voltages.

(3) **Effect of equal voltage drop** at no-load and full-load :—If the transformers in parallel have the same impedance volts, it follows that the magnitude of the current furnished by each will be inversely as its impedance. If further they have the same ratio of reactance to resistance, it follows that the currents delivered by each will have the same phase, and the total current will then be the numerical sum of the individual currents.

Given two or more transformers, having the same ratio of primary to secondary turns and having relatively

small magnetising currents, to be banked so as to operate in parallel; the division of the total load between them depends chiefly upon the total impedances between the busbars, including with each transformer its connecting wires and any meters or relays through which the current may pass. In any case where transformers banked in parallel do not divide the total load according to their rated capacities, A PROPER DIVISION OF THE CURRENT MAY BE EFFECTED BY INCREASING THE IMPEDANCE IN THE CIRCUIT of the transformer which delivers more than its share of the total current. This may be easily done by inserting a suitable choke coil (a coil of wire wound on a laminated iron core) in series with either its primary or secondary lead wires

When the ratio of reactance to resistance is unequal in the transformers, the phases of the secondary currents are not the same so that the transformers may deliver equal currents and still not deliver equal amounts of power to the circuit It follows that a wattmeter connected with its series (current) coils in circuit with only one of, say, two transformers of equal rating will not measure half of the total power. It will measure more than half or less than half

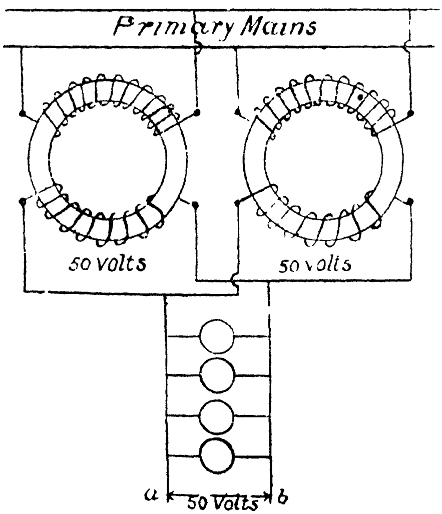


Fig. 234

according to the value of $cos\ \phi$ in the expression $EI\ cos\ \phi$, where

$$tan\ \phi = \text{reactance/resistance}.$$

(4) **Wrong Polarity**:—This may be considered as a greatly magnified case of (3). The resultant voltage in the local circuit between the secondaries is equal to the arithmetical sum rather than the difference of the secondary induced voltages. As the total impedance of this circuit is kept relatively small by careful design in order to avoid bad voltage regulation, this resultant voltage causes a current to flow which is enormous, relative to the rated current, and which must burn out the transformers if it does not open the fuses or other devices provided to protect the transformers against overload. The local current will flow whether the transformers are connected to a load or not and the load will be poorly distributed among the transformers.

(5) **Unequal percentage of impedance**:—The currents carried by the transformers, expressed as percentages of their respective rated full load currents, will be inversely proportional to their percentage of impedance. As the terminal voltages are practically the same for all transformers in parallel, the K V. A load in individual transformer, expressed as percentage of their respective rated K. V. A., will also be inversely proportional to their percentages of impedance. Thus, if transformer A has 4 per cent. impedance and B has 2 per cent. impedance, then when the total load is such that A carries 75 per cent. of its rated K. V. A. or rated current, transformer B must at the same time be carrying $\left(\frac{4 \text{ per cent.}}{2 \text{ per cent.}} \times 75 \text{ per cent.}\right)$ or 150 per cent. of its own rated K. V. A. or rated current in other words, B is operating at 50 per cent. overload when A is at $\frac{3}{4}$ load, and A is operating at half-load when B is at full load, regardless of what the actual K. V. A. value of those rated loads may be.

The impedance of a transformer is generally expressed as the voltage drop at normal load in percentage

of normal voltage. It is the resultant of two components: the resistance drop, and the reactance drop, which depends on the magnetic leakage between the high and low-tension windings and is 90° out of phase with the current.

Thus per cent. $IZ = \sqrt{(\text{per cent. } IR)^2 + (\text{per cent. } IX)^2}$.
where. IZ = total impedance drop;

IR = resistance drop of high- and low-voltage windings;

IX = reactance drop of high- and low-voltage windings.

The value of per cent. IZ is easily obtained by short-circuiting one winding and measuring the E.M.F. which must be applied at the terminals of the other winding to force full-load currents through the winding at normal frequency. The impedance may, therefore, be measured directly.

The resistance E. M. F. is equal to the high-voltage current multiplied by the equivalent resistance of the transformer, which may be obtained by measuring the resistance of both the high- and low-voltage windings, and, adding to the resistance of the high-voltage windings that of the low-voltage multiplied by the square of the ratio of transformation.

The reactance E.M.F. may be calculated from the known values for the impedance E.M.F. and resistance E. M. F. Thus—

$$IX = \sqrt{(IZ)^2 - (IR)^2}$$

In the majority of power transformers, the total resistance drop is small compared to the reactance drop, in which case the per cent. impedance drop (per cent. IZ) can be taken as approximately equal to the per cent. reactance drop (per cent. IX). In many lighting transformers, however, where the reactance is made as small as possible, this cannot be done without introducing considerable error.

The following formula may be used for finding the **division of load** between any number of transformer banks operating in parallel on single-phase circuits.

$$I_1 = \frac{\left(\dfrac{\text{K. V. A.}}{\text{per cent. } IZ}\right)_1}{\left(\dfrac{\text{K. V. A.}}{\text{per cent. } IZ}\right)_1 + \left(\dfrac{\text{K V A}}{\text{per cent. } IZ}\right)_2 + \ldots} \times I_L,$$

$$I_2 = \frac{\left(\dfrac{\text{K. V. A}}{\text{per cent. } IZ}\right)_2}{\left(\dfrac{\text{K. V. A.}}{\text{per cent. } IZ}\right)_1 + \left(\dfrac{\text{K V. A}}{\text{per cent. } IZ}\right)_2 + \ldots} \times I_L$$

where I_1 = load current in transformer bank No. 1;

I_2 = load current in transformer bank No. 2;

I_L = line current for any given load;

$\left(\dfrac{\text{K. V. A.}}{\text{per cent. } IZ}\right)_1$ = capacity rating of bank No. 1, divided by its per cent. impedance;

$\left(\dfrac{\text{K. V. A.}}{\text{per cent. } IZ}\right)_2$ = capacity rating of bank No. 2, divided by its per cent. impedance.

The above formulæ, however, are only correct when the relative ratio between the resistance and reactance of all the transformers are equal. If not, the sum of the individual load currents will be greater than the current in the line, due to a phase difference between the currents in the different transformers. The error introduced by the inequalities in the values of this ratio is generally so small that it can be safely neglected.

When there are only two units (or banks of similar units) having impedances different in magnitude and phase angle, the division of load can be calculated very

conveniently and accurately by the following graphical method :—

Lay out the two impedances per cent. $IZ' =$ (per cent. IR' + per cent. IX'), and

K_x per cent. $IZ'' = (K_x$ per cent. $IR'' + K_x$ per cent. $IX'')$, where

$K =$ K. V. A'. /K. V. A''.

Draw the resultant and call it I_L, the total load current in the lines. Then, per cent IZ' will represent I'', and K_x per cent. IZ'' will represent I' in magnitude and phase angle, because the currents in the units are inversely proportional to their respective impedances.

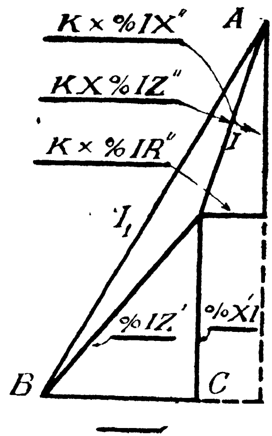


Fig. 2·35

(6) **Unequal ratios of reactance to resistance :—** If the ratio of (equivalent) resistance to (equivalent) reactance, or the ratios of resistance or reactance to impedance are not equal for all transformers, whose secondaries are interconnected in parallel, the result will be that the total K. V. A. of transformer capacity required will be greater than the total K. V. A. of load served from net work. This is because the currents and the K. V. A in different transformers will not be in phase with one another or with total load, and the power factor of individual transformers will not be equal to one another or to the resultant power factor of the load. If the transformers are very poorly selected, the resulting loss of load capacity and increase of energy losses in transformers and in connecting mains may become a very serious matter.

The distribution of load between two transformers A and B is as follows :—

$$\frac{\text{K. V. A. in } B}{\text{K. V. A. in } A} = \frac{\text{\% impedance of } A}{\text{\% impedance of } B} \times \frac{\text{Rated K. V. A. of } B}{\text{Rated K. V. A. of } A}$$

Note :—

(1) That compensation for difference in impedance may be made by adding external resistance to the transformers whose reactances and resistances are too low. The amount to be added in each case is that which will make up the percentage value of the reactance drop and the ohmic drop, at the rated currents the same in all transformers.

(2) If the ratio of transformation is different, compensation by external reactances cannot be used, but resort must be had to balance coils or auto-transformers.

(3) The auto-transformers may be used for producing proper distribution of load in all cases.

(4) When the transformation ratios of two transformers are slightly different, they may be operated in multiple without incurring much trouble.

From the above discussion it is evident that special care must be taken in banking transformers for parallel operation to see that the several units are delivering their proper share of the total current output. Furthermore, it is not safe to assume that transformers even of the same rated capacity and of the same make will share a given load equally when operated in parallel. The only safe procedure in such cases is to measure the voltage, current, and watts of the several transformers.

The division of load between any number of transformer banks operating in parallel on single-phase circuits may be found as follows :—

Example 10.—Transformers *A*, *B*, *C*, having characteristics, as tabulated below, are operated in parallel.

Determine :—

(*a*) Which transformer will reach its full-load first as the total load is increased?

(*b*) What will be the load on each of the other transformers, in K. V. A. and in percentage of its respective rated capacity, when the transformer of part (*a*) is operating at its full-rated capacity?

Transformer No.	H. T. volts.	L. T. volts.	Impedance volts in o/o	Impedance watts.	Total I^2R calculated from resistance.	Frequency	Rated K.V.A.	$\frac{\text{Rated K. V. A.}}{\text{Impedance}} = K$
A	3300	2200	2·2	2700	2000	50	440	200
B	3300	2200	2·5	3100	2850	50	440	176
C	3300	2200	4·2	5600	4200	50	630	150

(*c*) When transformer *C* having the highest percentage of impedance reaches its full-load, what will be load on *B* and *A*, respectively, in K. V. A. and in per cent. of their rated capacities ?

Solution.—(*a*) We have already explained that the transformer having lowest percentage of impedance (in this case, *A*) will be first to reach its rated full load as the total load is increased We have also seen that the transformer having highest percentage of impedance (in this case, *C*) will be the last to attain its rated full load.

(*b*) It should be evident from the preceding explanations that the actual loads, in amperes or in K V.A. on each of several transformers in parallel will be inversely proportional to the percentages of impedance and directly proportional to the rated values of K.V.A. or of currents.

Thus, in the above example, *C* will carry $\left(\frac{2{\cdot}2}{4{\cdot}2}\right)$ times its own rated K. V. A. when *A* is carrying just its rated K. V. A.; but in as much as the rated K. V. A. of *C* is $\left(\frac{630}{440}\right)$ times that of *A* it follows that the actual K. V. A. which *C* carries will be $\left(\frac{2{\cdot}2}{4{\cdot}4} \times \frac{630}{440}\right)$ times as

large as which A carries. Whatever may be the numerical value of these loads. Thus :—

$$\frac{\text{K. V. A. in } C}{\text{K. V. A. in } A} = \frac{\%\text{ impedance of } A}{\%\text{ impedance of } C} \times \frac{\text{rated K. V. A. of } C}{\text{rated K. V. A. of } A}$$

whence $$\frac{\text{K. V. A. in } C}{\text{K. V. A. in } A} = \frac{\dfrac{\text{Rated K. V. A. of } C}{\%\text{ impedance of } C}}{\dfrac{\text{Rated K. V. A of } A}{\%\text{ impedance of } A}} = \frac{K_C}{K_A}$$

where K is a factor obtained for each transformer by dividing its rated K. V. A. by its percentage of impedance.

Having calculated the values of K for transformer in this example, as shown in the last column of the table, we may state the following proportionality :—K. V A. of A : K. V. A. of B : K. V. A. of C : : 200 : 176 : 150 or that $I_A : I_B : I_C = 200 : 176 : 150$.

Thus, at any and all loads B will deliver $\left(\frac{176}{200}\right)$ times as many amperes as A. Therefore, when A is delivering its rated full load of 440 K. V A. or $\left(\frac{440000}{2200} = 200\right)$ amperes low-tension, C will be delivering $\left(\frac{150}{200} \times 200\right)$ or 150 amperes and B will be delivering $\left(\frac{176}{200} \times 200\right)$ or 176 amperes. But 150 amperes is only $\left(\frac{150}{630,000 \div 2200}\right)$ or 52·4 per cent. of the rated capacity of C and 176 amperes is only $\left(\frac{176}{440,000 \div 2200}\right)$ or 88 per cent. of the rated capacity of B.

(Check : $\frac{2\cdot2}{4\cdot2}=52\cdot4$ per cent. for C and $\frac{2\cdot2}{2\cdot5}=$ 88 per cent. for B).

(*c*) When C reaches its full load or 286·36 amperes low tension, B will be delivering $\left(\frac{176}{150}\times 286\cdot36 = 336 \text{ amperes}\right)$ or $\frac{4\cdot2}{2\cdot5} = 168$ per cent. of its rated capacity. while A will be delivering $\left(\frac{200}{150}\times 286\cdot36 = 381\cdot8 \text{ amperes}\right)$ or $\left(\frac{4\cdot2}{2\cdot2} = 190 \text{ per cent. of its rated capacity.}\right)$

Example 11.—Two 100 kW. single-phase transformers are connected in parallel both on the primary and secondary. One transformer has an ohmic drop of $\frac{1}{2}$ % at full load and an inductive drop of 8 % at full load zero power factor. The other has an ohmic drop of $\frac{3}{4}$ % and an inductive drop of 4 %.

Show how they will share the following loads :—

(*a*) 180 kW. at ·9 power factor.

(*b*) 120 kW. at ·6 power factor. (C. & G., Final)

Solution :—

(*a*) Since the transformers are connected in parallel, their terminal voltages on either sides must be the same in phase and in value.

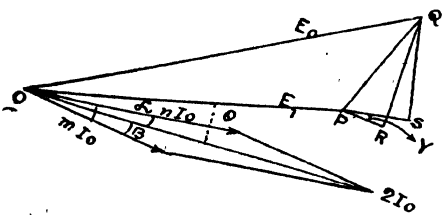


Fig. 2·36

They can, however, take different currents at different power factors, subject to the condition that the internal drop is the same vectorially in both.

The figure represents the impedance triangles PQR and PQS in a magnified form.

Let I_o represent the full-load current, W_1 the power, and mI_o current by the first transformer ; W_2 the power, and nI_o current by the second transformer; E_1 and E_0 the full-load and no-load voltages, respectively.

Now the angles PRQ and PSQ are right angles. PQ is the common drop ; therefore the points $PQRS$ are concyclic

Further, the ratios $= \frac{QR}{PR} = \frac{8}{\cdot 5} = 16$

$$\frac{QS}{PS} = \frac{4}{75} = \frac{16}{3}$$

$\therefore$ the angles SPR between nI_o and mI_o is always fixed and equals to—

$$\gamma = \tan^{-1} 16 - \tan^{-1} \tfrac{16}{3}$$
$$= 86^\circ{\cdot}44 - 79^\circ{\cdot}4$$
$$= 7{\cdot}04^\circ$$

Again—

$$PR^2 + QR^2 = PS^2 + QS^2 = PQ^2$$

$$\therefore \quad m^2 I_o^2 \left\{ (\tfrac{1}{2})^2 + 8^2 \right\} = n^2 I_o^2 \left\{ (\cdot 75)^2 + 4^2 \right\}$$

$$\therefore \quad m^2 I_o^2 (\tfrac{1}{4} + 64) = n^2 I_o^2 (16{\cdot}5625)$$

$$m^2 (64{\cdot}25) = n^2 (16{\cdot}5529)$$

$$\therefore \quad n^2 = 3{\cdot}8788\, m^2$$

$$\therefore \quad n^2 = 1{\cdot}9693\, m \quad \ldots \quad \ldots \quad \ldots \quad (i)$$

Next consider the resultant current for 180 kW at ·9 p. f.

K. V. A. $= \frac{180}{\cdot 9} = 200$ Therefore the total load current is 2 I_o.

$$n^2 I_o^2 + m^2 I_o^2 + 2\,nm\,I_o^2 \cos\gamma = 4\,I_o^2$$

$$n^2 + m^2 + 2\,n\,m\cos\gamma = 4$$

Substituting from (*i*) we get—

$m^2\ (3\cdot8788+1+2\times1\cdot963\times\cos 7\cdot04^\circ)=4$

$m^2\ (8\cdot78 = 4$

$2\cdot9631\,m = 2 \qquad \therefore\ m = 2\times\cdot3375$ and

$n = 2\times\cdot665$

If α is the angle between nI_o and $2\,I_o$ and β is the angle between mI_o

$$\frac{\sin\alpha}{\sin\gamma} = \frac{n}{2} \qquad \therefore\ \sin\alpha = \cdot0414$$

$$\alpha = 2\cdot38^\circ$$

$$\frac{\sin\beta}{\sin\gamma} = \frac{m}{2} \qquad \therefore\ \sin\beta = \cdot0815.$$

$$\therefore\ \beta = 4\cdot66^\circ$$

$W_1 + W_2 = 180 = K.\ 2\,I_o\cos\theta$

$\cos\theta = \cdot9$

$\theta = 25\cdot8^\circ$

$KI_o = 100$ kW.

$W_1 = K.\ m\,I_o\cos(\theta+\beta)$

$= K.\ m\,I_o\cos(30\cdot46)$

$= 100\times2\times\cdot3375\times\cos 30\cdot46^\circ$

$= 58$ kW. ....Load taken up by transformer No. 1.

$W_2 = K\,I_o\,n\cos(\theta-\alpha) \qquad \alpha = 2\cdot38^\circ$

$= 100\times2\times\cdot665\cos(23\cdot42)^\circ.$

$= 122$ kW. .... Load taken up by transformer No. 2.

(*b*) In this case the relation between m and n is the same. The total K.V.A $= \frac{120}{\cdot9} = 200$. Load current is the same, namely, $2\,I_o$.

Only $\theta = \cos^{-1} 0\ 6 = 53{\cdot}1$

α, β and γ are the same

so that,

$$W_1 = KI_o\, m \cos(\theta + \beta)$$

$$= 100 \times 2 \times {\cdot}3375 \times \cos(53{\cdot}1^\circ + 4{\cdot}66^\circ)$$

$= 36$ kW. Load of No. 1.

$$W_2 = K\, I_o\, n \cos(\theta - \alpha)$$

$$= 100 \times 2 \times {\cdot}665 \times \cos(53{\cdot}1^\circ - 2{\cdot}28^\circ)$$

$= 84$ kW. Load of No. 2.

As stated above, transformers operating in a three-phase delta-delta bank will take a circulating current if their ratios are different ; they will further fail to divide the load properly if their impedances and ratios of reactances to resistances are unequal.

36.—Calculation of circulating current.

Let per cent. I_c = circulating current in per cent. of normal load current.

Let per cent. E=Unbalanced voltage in delta approximately equal to the maximum difference in phase voltages in per cent. of the phase voltage. This applies to the headings within the delta, and not to any portion that may extend beyond the delta.

Let per cent. IZ = The per cent. impedance of one unit, assuming all three units alike.

Per cent. $I_c = 100 \times$ per cent. $E/3 \times$ per cent IZ.

This circulating current flows in both the primary and the secondary windings simultaneously

37.—It is not considered good practice to **operate a three-phase delta-delta bank** under any one of the following conditions:—

(1) When the division of load is such that, with a total load on the bank equal to the combined K. V. A. rating, the load current in any one of the units is greater than 110 per cent. of its rating

(2) When the no-load circulating current exceeds 10 per cent. of the rated current of the unit.

(3) When the arithmetical sum of the no-load circulating current and the load current exceeds 110 per cent. of the rated current of the unit.

The above-mentioned currents are exclusive of magnetising current and of each other.

Delta-delta-connected transformers having 50 per cent. taps brought out can supply two loads simultaneously ; one at 100 per cent. and the other at 50 per cent. voltage.

Where power is transmitted with delta-Y step-up and Y-delta step-down transformers on a solidly-grounded system, service may be maintained at reduced load with a transformer cut out from either the step-up or the step-down bank, or both When a transformer is cut out from each one of the two banks, they must be cut out from the same phase.

38. Calculation of load division if the per cent. impedance and K. V. A. capacities of all three of the phases are dissimilar.

Let (per cent K. V. A.)$_1$ = load in phase in per cent. of the total load on the lines.

Let (per cent. K. V. A.)$_2$ = load in phase No. 2 in per cent of the total load of the lines.

Let (per cent K. V. A.)$_3$ load in phase No. 3, and R_1, R_2, R_3 ; X_1, X_2, X_3 are the resistance and reactance ohms of the respective phases. If the rated capacity of the 3 phases are alike, then per cent. $(IR)_1$ may be substituted instead of R_1 (per cent. $IX)_1$ instead of X_1, etc.

If the rated capacities are also dissimilar,

Put $\dfrac{(\text{Per cent } IR_1)}{(\text{Rated K V A.})_1}$ for R_1.

Put $\dfrac{(\text{Per cent. } IX_1)}{(\text{Rated K. V. A.})_1}$ for X_1

Put $\dfrac{(\text{Per cent. } IR_2)}{(\text{Rated K.V.A.})_2}$ for R_2

Put $\dfrac{(\text{Per cent. } IX_2)}{(\text{Rated K. V. A.})_2}$ for X_2

$$(\text{Per cent. K. V. A.})_1 = 50\sqrt{\frac{(R_2+R_3 \pm 0.58\,X_2 \mp 0.58\,X_3)^2+(X_2+X_3 \mp 0.58\,R_2 \pm 0.58\,R_3)^2}{(R_1+R_2+R_3)^2+(X_1+X_2+X_3)^2}}$$

$$(\text{Per cent K. V. A})_2 = 50\sqrt{\frac{(R_3+R_1 \pm 0.58\,X_3 \mp 0.58\,X_1)^2+(X_3+X_1 \mp 0.58\,R_3 \pm 0.58R_1)^2}{(R_1+R_2+R_3)^2+(X_1+X_2+X_3)^2}}$$

$$(\text{Per cent. K. V. A.})_3 = 50\sqrt{\frac{(R_1+R_2 \pm 0.58X_1 \mp 0.58X_2)^2+(X_1+X_2 \mp 0.58\,R_1 \pm 0.58R_2)^2}{(R_1+R_2+R_3)^2+(X_1+X_2+X_3)^2}}$$

The upper algebraic signs refers to one-phase rotation, the lower signs to the opposite phase rotation. Load division and maximum capacity of the bank are thus dependent on the phase rotation.

39.—Maximum output and capacity of the bank is calculated by determining that the line K. V. A. will load a given phase fully. This being calculated for each phase, the maximum of the three line K. V. A., so calculated, represents maximum capacity of the bank without overloading any phase.

Thus to fully load the indicated phase the load on the lines will be—

$$\text{Line K. V. A} = \frac{100\,(\text{rated K. V. A.})_1}{(\text{Per cent. K. V. A.})_1}$$

$$= \frac{100\,(\text{rated K. V. A.})_2}{(\text{Per cent. K. V. A})_2}$$

$$= \frac{100\,(\text{rated K. V. A.})_3}{(\text{Per cent. K. V. A.})_3}$$

40. Possible methods of phasing out three-phase Transformers.—When phasing in any two transformers for parallel operation it is essential that they should possess the same polarity, the same phase rotation, and the same inherent phase angle difference between primary and secondary terminals. While the theory of parallel operation of a single-phase and polyphase transformers is essentially the same, the actual practice for obtaining suitable connections between any two single-phase tranformers is considerably simpler than the determination of the correct connections for, say, any two three-phase transformers.

41. Single-phase Transformers.—*Phase Angle Difference Between Primary and Secondary Terminals* :— In single-phase transformers this point does not arise, as by the proper selection of external leads any two single-phase transformers can be connected so that the phase angle difference between primary and secondary terminals is the same for each Consequently, the question really becomes one of polarity.

Polarity and Phase Rotation :—The term " polarity, " when used with reference to the parallel operation of electrical machinery, is understood to refer to a certain relationship existing between two or more units. Any two single-phase transformers have the same polarity when their instantaneous terminal voltages are in phase. With this condition a voltmeter across similar terminals will indicate zero.

Single-phase transformers are essentially simple to phase-in, as for any given pair of transformers there are only two possible sets of external connections, one of which must be correct. If two single-phase transformers, say, X and Y, have to be phased-in, the first procedure is to connect both primary and secondary terminals of, say, transformer X to their corresponding busbars, and then to connect the primary terminals of transformer Y to their busbars. If the two transformers have the same polarity, the corresponding secondary terminals will be at

the same potential, but in order to ascertain, if this is so, it is necessary to connect the one secondary terminal of transformer *Y* to what is thought to be its corresponding busbars. It is necessary to make the connections from one secondary terminal of transformer *Y* so that when taking voltage readings their is a return path for the current flowing through the voltmeter. The voltage across the disconnected secondary terminal of transformer *Y* and the other busbar is then measured, and if a zero reading is obtained, the transformers have the same polarity, and permanent connections can accordingly be made If, however, the voltage measured is twice the normal secondary voltage, then the two transformers have opposite polarity. To rectify this it is only necessary to cross-connect the secondary terminals of transformer *Y* to the busbars. If, however, it is more convenient to cross-connect the primary terminals, such a procedure will give exactly the same result.

In single-phase transformers the question of phase rotation does not arise, as this is a characteristic of polyphase transformers.

42. Polyphase Transformers.—*Phase-Angle Difference Between Primary and Secondary Terminals:*— The choice of suitable external connections which will enable two or more polyphase transformers to operate satisfactorily in parallel is much more complicated than as a similar choice for single-phase transformers, largely on account of the phase-angle difference between primary and secondary terminals of the various connections. In Fig. 2·37 is shown the range of three-phase connections commonly met with in practice, and the diagram is divided up into four main sections The pairs of connections in the groups of the upper left-hand section may be connected in parallel with each other, and those in the lower right-hand section may also be connected in parallel with one another, but the remaining pairs in the other two groups cannot be so connected as there is a 30° phase displacement between corresponding secondary terminals. This

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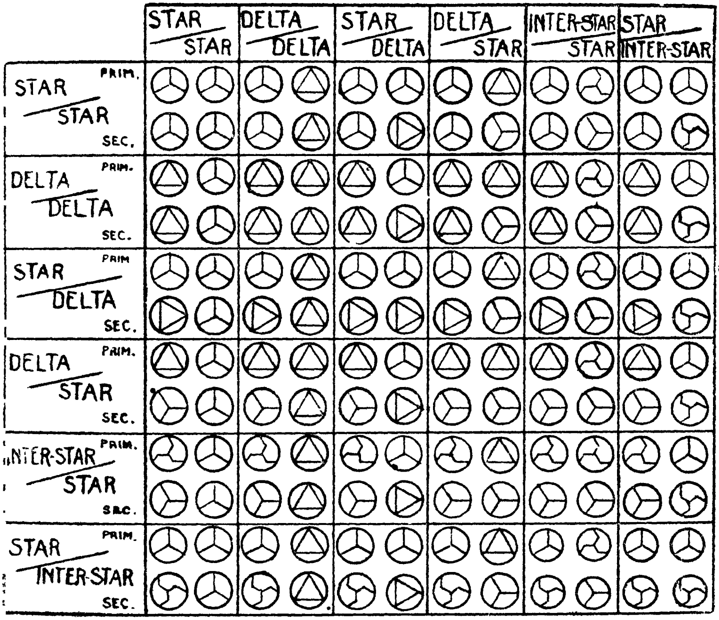


Fig. 2 37

displacement is indicated by the dotted lines joining the pairs of secondaries. It should be noted that this question of phase-displacement is one of displacement between the line terminals and not necessarily of any internal displacement which may occur between the vectors representing the voltage across the individual phase windings.

When phasing-in any two or more transformers, it is essential that both their polarity and phase rotation should be the same. It is generally advisable when installing two or more transformers for parallel operation actually to make a test for the purpose of definitely ascertaining that corresponding secondary terminals have the same instantaneous voltage magnitude and phase.

With regard to the actual procedure to be followed for determining the correct external connections. there are two ways in which this may be done. The first one is to place the two transformers in parallel on the primary side and take voltage measurements across the secondaries, while the other is to refer to the manufacturer's diagram.

Dealing first with the method in which a series of voltage readings are taken for the purpose of determining how the transformers shall be connected, we will assume two transformers X and Y having the same voltage ratios and impedances and with their internal connections corresponding to any one pair of the permissible combinations of the diagram. The first procedure is to connect all the primary terminals of both the transformers to their corresponding busbars, and to connect all the secondary terminal of one transformer, say, X, to its busbars Assuming that both secondary windings are unearthed, it is next necessary to establish a link between the secondary windings of the two transformers, and for this purpose any one terminal of transformer Y should be connected *via* the busbars, to what is thought to be the corresponding terminal of the other transformer. Voltage measurements should now be taken across certain terminals, and if in both instances zero readings are indicated, the transformers are of the same polarity and phase rotation, and permanent connections may now be made

to the busbars. If, however, such measurements do not give zero indications, it is, generally, advisable to take, in addition, further measurements between other terminals, as such measurement will enable one to lay out the exact vector relationship of the voltages across the two transformer secondary windings with greater facility.

In case of transformers, of which the primary and secondary connections are different, such, for instance, as delta/star, it is only necessary, when one of the transformers is of opposite polarity and cannot be phased in unless their internal connections are reversed When the phase-rotation is opposite, it is only a question of changing over the lettering of the terminals of one transformer, and provided the polarity is correct, connecting together similar lettered terminals With two transformers both having star-connected secondaries the preliminary common link between the two can be made by connecting the star points together, and this leaves all terminals free for the purpose of making voltage measurements. As a rule, this procedure makes the result much more apparent at first glance owing to the increased number of voltage measurements obtained.

Dealing next with the method in which the transformer manufacturer's diagram is relied upon for obtaining the correct internal connections, one of the figures in the diagram will show the six most common combinations of connections for the three-phase core-type transformers measured according to present practice. It is to be noted that the vectors indicate instantaneous induced voltage, as by arranging them in this way the vector diagram apply equally well, irrespective of which winding is the primary and which the secondary. Both primary and secondary coils of the transformers are wound in the same direction when looking on top of the coils. With the standard polarities shown it is only necessary to join together the similarly-placed terminals of transformers which have connections which will allow of parallel operation, to ensure the choice of the correct external connections. That is, there are two main groups only, the first comprising the star/star and the delta/delta.

connections, while the other consists of star/delta, delta/star, interconnected star/star and star/interconnected star

Other figures show, for the various combined primary and secondary connections, the external connections which will, and which will not, enable satisfactory parallel operation to be given when the primary and secondary coils of each transformer or bank are wound in the same direction The diagrams apply equally well irrespective of whether the coils are all wound in a clockwise or counter-clockwise direction

The diagrams have been drawn on the basis of comparison between two transformers, the external connections to busbars of one of which are maintained constant, while the external connections of the second transformer are varied to give every possible combination Further, the internal connections between phases of the one transformer have also been maintained, unaltered while those of the second transformer have been varied so forming four distinct groups to each diagram That is, the second transformer has, in group 1, standard meshing both on primary and secondary sides; in group 2, standard primary and reversed secondary meshing; in group 3, reversed primary and standard secondary meshing; while in group 4, the meshing is reversed on both primary and secondary sides With any two transformers, therefore, there are 24 different cases to consider depending upon the internal meshing and the external connections to busbars.

A study of the figures last mentioned will reveal the fact that where the connections on the primary side are the same as those on the secondary side (*i.e.*, the case of star/star or delta/delta) in two of the four groups (*i.e.*, groups 1 and 4) all the six possible external connections in each will result in satisfactory parallel operation, while in the remaining two groups (*i.e.*, 2 and 3) satisfactory connections cannot be obtained unless the internal meshing on one side of one transformer is reversed. In the cases where the primary and secondary connections are dissimilar, as with Y/delta or delta/Y, suitable external connections can be chosen from each

of the four groups, but only three connections out of each group will give the desired conditions. Those pairs of the external connections to busbars are correct, which result in producing vector diagrams, so that the ends of the vectors which represent the primary and secondary terminals coincide with one another.

Particular attention is drawn to the fact that any two transformers having dissimilar primary and secondary connections may always be phased in satisfactorily without having to interfere with the internal connections, irrespective of the order of the internal meshing or of the direction in which the coils are wound. With transformers each having the same primary and secondary connections it is not always possible to obtain the correct external connections without having to reverse the internal meshing between phases on one side of one of the transformers.

In some cases there is the difference that the primary and secondary coils of each transformer or bank are wound in the opposite direction, though the corresponding coils (*i.e.*, primary or secondary) of both transformers or banks are wound in the same direction The advantage of having two separate series, set out in this manner, is, that in addition to comparing transformers in which corresponding coils are wound in the same direction, we can also compare one transformer in which both primary and secondary coils are wound in the same direction with another transformer in which the primary and secondary coils are wound in opposite directions.

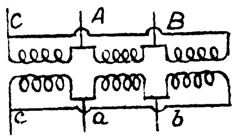
Two transformers of similar internal connections have been compared, that is to say a star/star with a star/star or delta/delta with a delta/delta, but as all the connections have been compared in the same way it is an easy matter to compare the connections of any two transformers in which the internal connections are dissimilar and of which the primary and secondary windings of each are not wound in the same direction. It should again be borne in mind that any two transformers will operate in parallel if the extremities of the vectors representing the terminals coincide, but not otherwise.

It is not essential that the vectors representing the voltages across the windings between any two terminals shall coincide ; an instance of this is the paralleling of a star/delta transformer with a delta/star in which case both primary and secondary terminals of the vector diagrams can be made to coincide, but the vectors representing the primary and secondary phase voltage will not coincide on either side.

43. Relative advantages of Y and △ connections in Transformers.—The general and fundamental arguments may be summed up as follows :—

With a △△-system, the advantages are that if one transformer becomes disabled, the system may be operated from the other two, operating on open delta

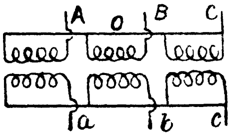
If the load is unbalanced, the voltages do not become unduly unbalanced. Resonance cannot occur. On the other hand, each transformer must be insulated for full-line voltage as there is no neutral to ground ; and if one line becomes grounded, the voltage strain on the rest of the system becomes 1·73 times the normal strain, and this strain may extend to the low-tension winding and the generator which is connected to the transformers.



Delta-Delta Connections.
Fig. 2·37

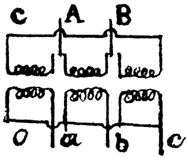
With YY-connection there is a very unstable neutral and possible excessive voltage strain on one phase, unless the neutral is grounded.

With a △ Y arrangement for step-up transformers, the neutral on the high-tension side may be grounded. The voltage strain on any transformer is then limited to 58 per cent of the line voltage. There is a possibility of operating the remaining two transformers, if one becomes damaged, using the neutral as a third conductor.



Star-Star Connections.
Fig. 2·38

However, there is the possibility of resonance under certain circumstances and the danger of causing disturbances in nearby telephone and telegraph circuits. Any accidental ground on the system makes a definite short-circuit on phase.



Delta-Star Connections.
Fig. 2'39

The arrangement of Y △ for step-up transformers is not desirable on account of the unstable neutral with unbalanced load, but is permissible with a balanced load or with a good connection from neutral of transformers to neutral of generator. This connection, however, is frequently used for step-down transformers particularly when connected to a balanced load.

Delta-connected transformers are used for practically all low-voltage distribution. The Y to delta connection is often used for high-voltage work, the transformers being Y-connected on the high-voltage side.

44. Grounded Neutral *versus* **Ungrounded Neutral.**—In any system without a grounded neutral there are numerous possibilities of disturbances resulting in a high-voltage strain on the various parts of the insulation of the system. With the high voltages now in use for transmission systems these disturbances may give a great deal of trouble by breaking down the insulation, as it is not always possible to employ a large margin of safety devices, and lightning arresters do not always protect from these disturbances. On the other hand, if the neutral is grounded, most of these disturbances will merely result in an excessive current, and if the circuit breakers are installed in the proper places, they will open the circuit, so that the only adverse result will be a temporary interruption of service.

The choice is then between a system with ungrounded neutral and a large margin of safety in the insulation, and a system with grounded neutral, moderate insulation and the possibility of occasional interruption of service.

45. Tertiary Winding :—(*a*) It permits a path for the flow of the third harmonic component of the magnetising current, which in a star-connected bank of transformer is a zero phase sequence system of currents, and would, if the delta connection were absent, find path through the neutral point and capacitance to ground of the trans mission lines, and cause inductive disturbances.

(*b*) In case of a ground on the system it permits enough current to flow to operate the protective apparatus.

46 The effect of the tertiary delta in eliminating the flow of third harmonic currents through ground.

(*a*) *First consider the neutral point isolated:*—Then the third harmonic component of the magnetising current can flow only in tertiary delta and, therefore, encounters the virtual impedance of this winding only. The limiting value for the third harmonic E M F. of neutral to ground is, therefore, the product of the harmonic component of the magnetising current of the tertiary winding at normal induction, and its virtual impedance multiplied by the proper transformation ratio.

(*b*) *Secondly consider the tertiary delta open and neutral point grounded* —Then the limiting value for the third harmonic current that will flow will depend upon the character of the external admittance and may be considerably greater than the third harmonic of the magnetising current under normal conditions.

(*c*) *Lastly consider the neutral grounded with tertiary delta closed.*—Then the action may be regarded as arising within the core in the form of a third harmonic E. M. F. causing current to flow both through the neutral to ground by way of the external admittance to ground and around the tertiary delta. The equivalent simple circuit is shown in Fig 2·40 and consists of the equivalent circuit transformer short-circuited at the end representing the tertiary and shunted on the grounded neutral side by admittance representing the external admittance of the system to ground. The limiting value of current that can flow in the joint circuit due to an internally set up third harmonic E. M F. is equal to that of the third harmonic component of the magnetising

current under normal conditions. But condition of resonance may exist between the tertiary virtual reactance to ground, such that the joint part may have a very high impedance to the flow of the third harmonic current. In this case *the limiting value of the current that can flow in the neutral* will be obtained by dividing the third harmonic component of E. M. F obtained with tertiary delta open, and neutral ungrounded by sum of the virtual impedance of the winding to be grounded and external impedance of one wire to ground.

(*d*) *Where two-coil transformers* are used and both windings are grounded, there are three possible paths for the flow of the third harmonic magnetising current, namely, the delta tertiary and the two paths through the neutrals of each winding.

In star-star connected three-phase core-type transformers the third harmonic component of the E. M. F. becomes very small due to the mutual inductance between phases, yet it is advisable to provide such transformers with delta-connected tertiaries.

47. The second function of the tertiary windings—It is expedient to estimate the amount of current that will flow through ground when one of the high-voltage lines becomes grounded. Take the simplest case

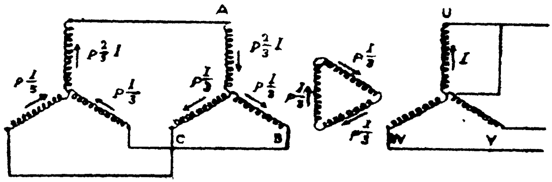


Fig. 2·40

and suppose a step-up being supplied with an alternator. Let the ratio of transformation be P and let the impedance to positive and negative phase-sequence of the alternator be ZA_1 and ZA_2, respectively, and let the internal generator voltage be EA_1. Let both the high-voltage and low-voltage neutrals of the transformer be grounded, but let that of the alternator be ungrounded.

Two impedance measurements are required for the transformers the short-circuit impedance measured on the high voltage side with the tertiary open-circuited, and the short-circuit impedance with tertiary closed, the low voltage winding being open. Let these be denoted by Z_T and Z_{T_0}, respectively. At the point of short circuit we shall have the ground currents in the high voltage phases O, Q, R, respectively, I, O, and O ; I resolved into its symmetrical components gives—

$$I_{P_0} = \frac{I}{3},\ I_{P_1} = \frac{I}{3} :\ I_{P_2} = \frac{I}{3} \quad \ldots (1)$$

We obtain for the value $I/3$

$$I/3 = \frac{\rho E A_1}{Z_{T_0} + K^2 (ZA_1 + ZA_2) + 2Z_T}$$

Find a value of $I'/3$ or $I/3$ for a tentative value $E'A_1$ of EA_1. Then the E.M.F across phase AB of the low-voltage winding will be—

$$Ec' = j\sqrt{3} \left\{ aE'A_1 - \frac{I'}{3} (aZA - a^2 ZA_2) \right\}$$

If Ec be the effective value at which the voltage across AB is held, $EA_1 = \frac{Ec}{Ec'} E'A_1$ and from this the true value of $I/3$ may be obtained The currents in the high- and low-voltage windings of the transformer and in the tertiary winding may then be estimated.

These are shown in Fig. 2·40. It has been assumed that the tertiary winding has the same number of turns as the low-voltage winding

If the supply instead of being directly from an alternator in a transmission line fed from an alternator through a transformer, the impedance of the transmission system should be added to ZA_1 and ZA_2 after they have been multiplied by the proper transformation factor.

The star-star connection with open delta-connected tertiary winding overcomes most of the objections

to the simple *Y*-*Y* connection. Tertiary winding in every unit is an independent winding having low impedance. These windings may be used to supply load at low voltage other than primary and secondary voltage.

An important application of the tertiary winding is to transform power from line voltage to transformer station voltage and at the same time supply power from the tertiary winding directly to synchronous condensers The condensers either supply leading K. V. A. to correct the power factor of the low-voltage system or supply the leading or lagging, K. V. A., necessary for the regulation of the line itself. The tertiary winding may also supply power to secondary networks. The cost of a single transformer bank for supplying power at different voltages is much less than that of two separate banks of the same total, K V. A., rating. Therefore the use of the tertiary winding may be adopted for purely economic reasons. The closed delta-connected tertiary stabilises the neutral and hence corrects the inherent drawback of of the *Y Y* connection. Furthermore, it supplies the third harmonic components (and the odd multiples) of the magnetising current and thus practically eliminates third harmonic, E. M. Fs., in the *Y*-coils. This is often needed with a system of grounded neutral as else the third harmonic currents would flow over the line and through the ground, possibly causing inductive disturbance to circuits.

The closed delta tertiary also reduces the impedance of the transformer to a value as for a phase to ground short circuit. This permits the flow of sufficient current to operate the protective devices.

The K. V. A. capacity of such windings is usually based on the short-circuit capacity and varies from 20 to 35 per cent. and sometimes to 50 per cent. of the name plate rating of transformer. It requires 300 to 400 per cent normal current to operate relays and tertiary winding should be designed to carry this current without dangerous temperature rise until the relay and circuit-breakers operate.

48. Elimination of Third Harmonic in Transformer.—The third harmonic voltage is practically eliminated under the following conditions :—

(1) When the tertiary delta winding is provided.

(2) When the primary neutral is connected to that of the generator.

(3) When the neutral of either side, primary or secondary, is connected to the neutral of a *Y*-delta bank across the lines on the same side.

(4) When the secondary is diametrical and is connected to a rotary converter.

49. Y-Y-Delta.—Delta-connected tertiary windings may be used in *Y-Y*-connected transformers for any of the following purposes :—

(1) To protect the transformer and system from excessive third harmonic potentials. The tertiary winding may be designed to carry only the third harmonic magnetising current ; the reactance between the primary and tertiary must be high enough to limit to a safe value the circulating current that would be produced in the tertiary to a line to neutral short circuit.

(2) To protect telephone interference due to third harmonic currents in the lines to ground Telephone interference is proportional to the ampere miles of the ground current. Thus it is possible that with a low impedance ground, a three-phase core-type transformer with a three per cent. residual voltage will produce practically as much unbalanced ground current as a bank of single-phase transformers with a 80 per cent. inherent third harmonic voltage.

A properly designed tertiary winding may, therefore, be essential in order to eliminate these disturbances.

(3) To stabilise the neutral of the fundamental frequency voltages.

Low reactance between the primary and tertiary winding is essential for the stability of the neutral, as it is inversely proportional to this reactance. The degree of stability required depends upon the purpose for which the neutral is to be used.

(*i*) If the tertiary winding is intended to stabilise the neutral when a single-phase load is taken from the line to the neutral or under conditions of unbalanced load or a four-wire three-phase system, the load in each phase of the tertiary is equal to one-third of the single-phase or unbalanced load, and at this load the reactance drop between the primary and tertiary should not be excessive

If the unbalanced load is only a small fraction of the transformer rating, a three-phase core-type unit may be used without a tertiary winding, provided that the reactance drop is not excessive.

(*ii*) If the tertiary winding is intended to hold a stable-grounded neutral on a otherwise isolated system, then the reactance should be as low as possible and the tertiary winding should be capable of withstanding the short-circuit current which will be limited only by the impedance of the generating system.

If the ground and short circuit are on the excited side, the short-circuit current is equal to—

$$I_s = \frac{100\ I}{\text{Per cent. } IX_{PT}}$$

where, I = normal current

IX_{PT} = Impedance between primary and tertiary.

I_s = short-circuit current in the tertiary.

If the ground and short circuit are on the secondary of the transformer, then the short-circuit current in the tertiary is equal to—

$$I_s = \frac{100\ I}{\text{Per cent. } IX_{PS} + \text{per cent. } IX_{PT}}$$

Provided that the tertiary is not between primary and secondary windings. If the tertiary is between primary and secondary windings, then—

$$I_s = \frac{100\ I}{2 \times \text{per cent. } IX_{PS} + \frac{1}{3} \text{ per cent. } IX_{TS}}$$

where, IX_{PS} = impedance between primary and secondary.

IX_{TS} = impedance between tertiary and secondary.

(*iii*) If the step-up transformers are isolated and high voltage of the step-down transformers is grounded, a tertiary winding may be used in the latter to permit a design for reduced test voltage. Under this condition, the neutral of the transformer should be solidly grounded and the reactance between the high voltage and tertiary windings should not be more than the impedance of the system on the generator side of the step-down transformer

(*iv*) If the neutral of the step-up transformers is solidly grounded, and if the neutral of the high-voltage winding of the step down transformers is also grounded and the latter is equipped with a tertiary winding, the short-circuit current in the tertiary due to a line ground is equal to

$$I_s = \frac{100}{3 \times \text{per cent. } IZ}.$$

which shows that the short circuit current is one-third of what it would be if the step-up transformers were isolated.

(4) To supply a load in addition to any of the above purposes.

Together with the above purposes the tertiary windings are sometimes made use of also to supply a load, frequently a condenser load for power factor correction. In such cases, there is the possibility of a short circuit on the lines of the tertiary windings also. Hence, a tertiary windings intended to support a load must be so designed as to be able to withstand a short-circuit on its own lines as well as short circuits on other windings.

50. The Pros and Cons of Transform :—

(*a*) Switching in a transformer on the primary side with secondary circuit open.

(*b*) Switching in with the secondary circuit closed on to a feeder.

(*c*) Switching out a transformer on load, or opening the feeder switch first and then switching out transformer— either method being allowable.

(*a*) If a transformer is switched on in the primary side with the secondary open circuited, a rush of current will ensue, the magnitude of which will depend upon the pressure of the primary circuit, the induction density for which the magnetic circuit is designed, the point of the pressure wave at which the switch is closed and the value of remnant magnetism in the transformer core. If the switch is closed at the instant when the pressure wave passes through its zero value, the flux density will reach, in the first half cycle, twice its normal maximum value, and it will gradually die down to the normal value disposed symmetrically on either side of the zero axis On account of the shape of the B.H. curve of transformer iron, the current corresponding to twice the normal maximum induction is very many times the normal no-load current, and this accounts for the transient current rush usually experienced when switching open-circuited transformer on to a live source. If there is a remnant magnetism in the core, the current rush is augmented or diminished according to the polarity of the remnant magnetism

If the switch is closed when the pressure wave is passing through its maximum value, no current rush is experienced provided there is no remnant magnetism present, as at this instant the flux in the core should normally be zero, and this condition is satisfied. It is, of course, only sometimes possible to switch in single-phase transformers without current rush, but with poly-phase transformers a rush of some sort is unavoidable, as the various phases reach their maxima at different periods of time.

(*b*) If the secondary side of the transformer is first connected to a cable or overhead line, the conditions outlined above are modified chiefly by the capacity current which would be drawn from the supply by the secondary line. The capacity current taken by the line would lead the E. M. F. by approximately 90° degree, and the resulting primary current rush would be a combination of the line capacity current and the transformer no-load current. So far as the pressure in the common use, it is doubtful whether there is very much

difference when switching in a transformer under the conditions discussed. On the other hand, it has been proved to be of distinct advantage to switch a transformer in through a length of cable on the primary side, as this materially reduces high pressure concentration.

(c) When switching a transformer out of circuit on no-load the tendency exists for the magnetic flux in the core to collapse suddenly, so causing high transient pressure rises. If, however, the secondary side of the transformer is closed through a load, this tendency to sudden collapse of flux is diminished, so that if other practical conditions permit, it is preferable to switch a transformer and load off together There are, of course, many users who first remove the load from the transformer and then switch the transformer out of commission, and while such a procedure has apparently given no ill results, the method recommended above is preferable

51. Three-Phase Open Delta or V Connection.—This system consists in omitting one transformer from the delta connection, and is used to save expense, particularly in temporary installation or in new installations where the load is not great at first, but is expected to increase in time. Thus the purchase and installation of the third transformer is postponed until the load requires it. The third transformer may be added as soon as the load increases beyond the capacity of the

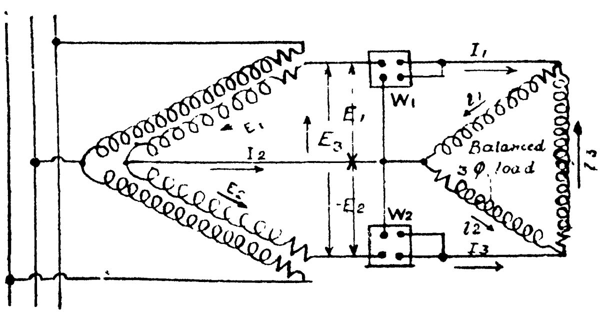


Fig. 2·41

two transformers. This connection can only be recommended for low voltages, such as 2300, as it is liable to produce dangerous potentials due to electrostatic unbalancing The regulation and efficiency are also poor, as one phase of the load receives its power from two transformers in series. The aggregate capacity of the two transformers should be 15 per cent. greater than the load Two transformers in open delta will heat faster for the same load than where they are in the closed delta connection

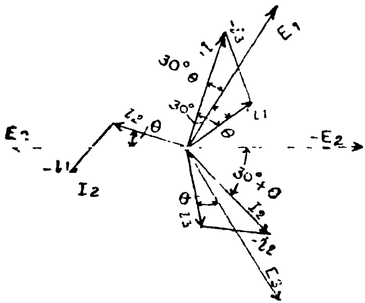


Fig. 2 42

For the connection shown in the figure 2 41 the same current flows through the transformer as in the current coil of the wattmeter, and hence the same as in the mains instead of in the circuits as would be the case with three transformers connected in delta.

If the connection of the voltage coil for wattmeter W_1 be taken as indicated by the arrows in the figure, then the connection for wattmeter W_2 is in the reverse direction.

$$W_1 = E_1 I_1 \cos (30^\circ - \theta)$$

$$W_2 = E_2 I_2 \cos (30 + \theta)$$

$$\text{Total power} = E_1 I_1 [\cos (30^\circ - \theta + \cos (30^\circ + \theta)]$$

$$= 2EI \cos \theta \cos 30^\circ$$

$$= 2EI \cos \theta \times 0{\cdot}867.$$

Hence, the capacity is reduced to 86·7 per cent. of the full-load rating, so that the two transformers in open delta will carry, with the same rise in temperature only $86{\cdot}7 \times \frac{2}{3} = 57{\cdot}7$ per cent. of the load carried by the three transformers in closed delta.

Note that the load is balanced and hence

$$i_1 = i_2 = i_3$$
$$I_1 = I_2 = I_3$$
$$\theta_1 = \theta_2 = \theta_3.$$

In the delta-connection there will be no interruption in the low tension service. The E M. Fs. between any two lines will remain approximately equal to each other as when the delta was complete and approximately 120° apart as to phase in the sequence indicated.

If one of the transformers is removed entirely from the system without interrupting the service on the low tension mains, the current in each of the two remaining transformers is compelled to increase to a value $\sqrt{3}$ times as great as the current carried by each of the three transformers in closed delta, carrying the same load. The removal of one transformer would cause each of the remaining to carry 173 K.V.A. without altering the total load appreciably. But the rated capacity of each being 100 K.V A. the total load must be reduced to $\left(\frac{100}{173}\right) \times 300$ or 173 K V.A. or the load in the each must be reduced to $100 \times \left(\frac{100}{173}\right)$ or 58 K.V.A otherwise they will be over loaded and heated up too much, *i.e.*, the rated capacity of those transformers must be such that they can deliver 173 K V.A and thus if we are to supply the load of 300 K. V A. we must have two such transformers having a total capacity of $2 \times 173 = 346$ K.V.A.

With delta-connected shell-type transformers to operate in open-delta when one phase becomes damaged, the damaged phase should be disconnected from the rest and short-circuited on itself to prevent the fluxes of other phases from inducing voltage in the damaged winding. In the three-phase core-type transformer it is possible to operate open-delta, but only when the damaged winding is open-circuited and is capable of withstanding normal voltage.

With the Δ connection the current in each transformer is 30° out of phase with the transformer voltage, so that each transformer under non-inductive load operates at only 86·6 per cent power factor. Based on a three-phase load, the cutting out of one transformer would, therefore, reduce the current-carrying capacity not to two-thirds of 100 per cent. which equals 66·6 per cent, but to two-thirds of 86·6 per cent. which equals 57·7 per cent. *Vide* p. 94.

Example 12. A 1000-volt 25-cycle 1000 K. V. A. three-phase delta-connected alternator, while operating at full-load on a circuit of 85 per cent. power factor, has one of its coils burnt out. With this coil open circuited (1) What is the maximum balanced load on a circuit of 85 per cent. power factor which the machine can supply continuously ? (2) What proportion of this load is supplied by each of the two remaining coils ?

Solution.—

(*1*) Total power delivered in watts $= 1000 \times {\cdot}85$
$= 850$ kW

when one coil is burnt
the total power $= 2/3 \times 850 \times 0{\cdot}867 = 491{\cdot}3$ kW.

$$(2) \quad \frac{\text{The load supplied by one coil}}{\text{The load supplied by the other coil}} = \frac{Cos\,(30+\theta)}{Cos\,(30-\theta)}$$

$$= \frac{Cos\,(30+31^\circ 25')}{Cos\,(30-31^\circ\ 25')} = \frac{4784364}{9996943} = \frac{1}{2.08}$$

Hence, the total power supplied by the two coils is divided in the ratio of 32·1 and 67·9 per cent.

Example 13. The load on a 2400-volt three-phase line consists of 2400, $\frac{1}{2}$ amp., 120-volt lamps on three circuits, and 300 h. p. of three-phase motors with an average power factor of 80 per cent. and an average efficiency of 88 per cent. all on one circuit. Draw the diagram of connections, specify the transformers, and find the current in the mains and also the resultant power factor.

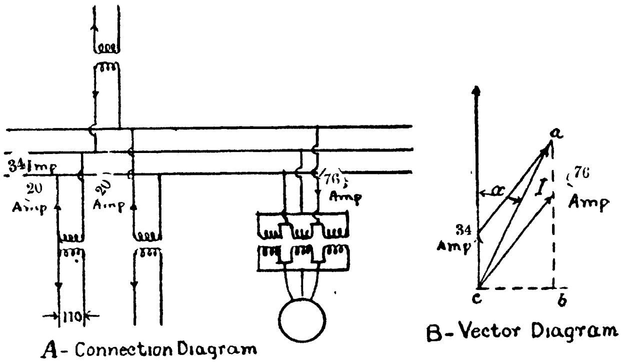


Fig. 2·43

Solution :—

The K. V. A. output of each motor transformer

$=1/3$ (motor K V.A)

$=1/3\ (300\times{}^{\cdot}746\times 1/{}^{\cdot}88\times 1/\ 8)=105{}^{\cdot}96$ K.V.A.

The line current for the motors

$=3\times 105{}^{\cdot}96\times 1{,}000/1{}^{\cdot}73\times 2{,}400=76{}^{\cdot}5$ amps.

The K.V.A. output of each lighting transformer

$=800\times{}^{\cdot}5\times 120/1{,}000=48$ K.V.A.

The primary current in each transformer

$=48{,}000/2{,}400=20$ amp.

but these transformers form a delta-connected load on the line, therefore the current in each line—

$=1{}^{\cdot}73\times 20=34{}^{\cdot}6$ amp.

The resultant current in the line is the resultant of 34·6 at 100 per cent. power factor and of 76·5 at 80 per cent. power factor and is equal to

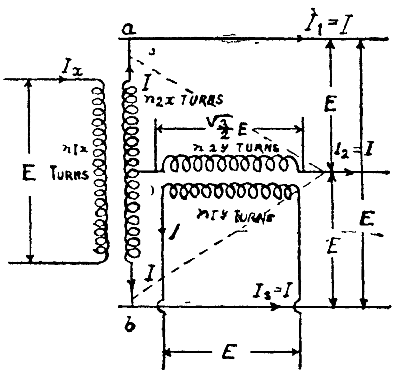
$$I=\sqrt{ab^2+bc^2}$$
$$=\sqrt{(\,{}^{\cdot}8\times 76{}^{\cdot}5+34{}^{\cdot}6)^2+({}^{\cdot}6\times 76{}^{\cdot}5)^2}$$
$$=\sqrt{11284{}^{\cdot}45}=106{}^{\cdot}2 \text{ amp.}$$

The power factor $=ab/ac=({}^{\cdot}8\times 76{}^{\cdot}5+34{}^{\cdot}6)/106{}^{\cdot}2$

$=(61{}^{\cdot}2+34{}^{\cdot}6)/106{}^{\cdot}2=95{}^{\cdot}8/106\ 2=90{}^{\cdot}01$ per cent.

52. Phase Transformation. Scott-Connection

To determine the current and voltages in a Scott-connected group of transformers to transform from two-phase E to three-phase E volts, Fig. 2·44.

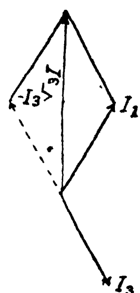


A

Voltage and current relation in a Scott-connected Bank of Transformer.
Fig 2·44

As the load is balanced I_1, I_2, and I_3 are all equal and the K. V. A. output on the three-phase side $= 1·732\ EI$.

The magnetising effect of the primary of a transformer being always equal to the magnetising effect of the secondary.



B

Vector Diagram
Fig. 2 45

$$n_{1y} \times I_y = n_{2y} \times I.$$

$$\therefore\ n_{1y}/n_{2y} = E/\sqrt{\tfrac{3}{2}}E$$

$$I_y = I \times \sqrt{3}/2.$$

The current oa in transformer $X = I$, and that in $ob = I$, but these currents are out of phase by 120 degrees and are in opposite directions. Hence, the resulting magnetising effect is not equal to $n_{2x}I$, $but = n_2 \times I \times \sqrt{3}/2$. But $n_{1x}/n_{2x} = E/E = 1$

and $n_{1x}I_x = n_{2x}I \times \sqrt{3}/2$

$\therefore\ I_x = I \times \sqrt{3}/2 = I_y.$

And the total two-phase K. V. A. $= 2\ E\ I_x = \sqrt{3}\ E\ I$, the same as on the three-phase side.

Example 14.—If a 100 h. p, 450-volt, three-phase motor is supplied from a 3,300-volt two-phase line, find the current I and also the current I_x and I_y if the efficiency of the motor is 90 per cent. and the power factor is 88 per cent.

Solution :—

Motor output $= 100 \times 0{\cdot}746 = 74{\cdot}6$ kW.

Motor input $= 74{\cdot}6/0{\cdot}9 = 82{\cdot}9$ kW.

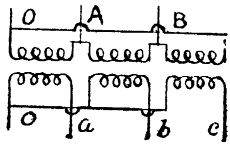
$= 82{\cdot}9/0{\cdot}88 = 94{\cdot}2$ K. V. A

$$= \frac{1{\cdot}73 \times E \times I}{1000} \text{ K.V.A.}$$

$$= \frac{1{\cdot}73 \times 450 \times I}{1000} \text{ K.V A.}$$

$\therefore I = 94{\cdot}2 \times 1000/1{\cdot}73 \times 450$

$= 121$ amperes.



Scott Three-phase to Two-phase Transformation.

Fig. 2·46

Neglecting transformer losses, $2 \times 3300 \times I_x = 94{\cdot}2$ K. V. A.

$\therefore I_x = 94{\cdot}2 \times 1{,}000/2 \times 3{,}300$

$= 47{,}100/3{,}300 = 14{\cdot}3$ amperes.

Example 15.—The coil *ab* in Fig 2·47 has 2,400 turns and the coil *cd* has 2,000 turns. The E. M. Fs. of *ab* and *cd* are each equal to 6,600 volts and one 90° out of phase with other. How would the taps *c* and *e* be located with respect to *ab* and *cd*, respectively, in order to obtain three-phase with 2,200 volts between any two line wires? Where should the three-phase line wires be connected to the coils?

Solution.—There are two solutions, as illustrated by Figs. 2·47, 2·48 and 2·49, in which the following relations held :—

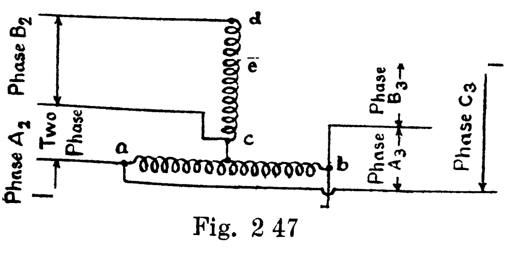


Fig. 2 47

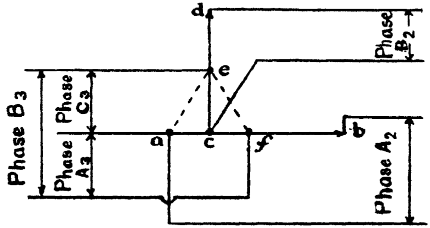


Fig. 2·48

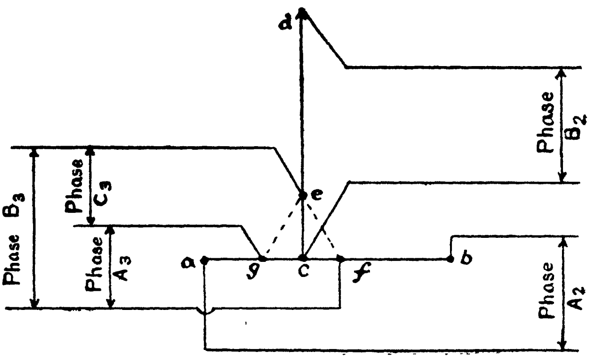


Fig. 2·49

Practically, the only difference between these two schemes is that Fig. 2·49 requires four taps to be made in the autotransformers or transformer secondaries, whereas Fig. 2·48 requires only three taps to be made.

Fig. 2·49.—This method requires four taps, *g*, *c*, *f* and *e*, to accomplish the same result as is shown in Fig. 2·48.

Example 16.—What transformer capacity in K.V.A. would be required to transform 2,200 volts two-phase to 2,200 volts three-phase delivering a balanced non-inductive load of 450 K. V. A. from the three-phase terminals ?

Solution.—K. V. A. delivered at each of three external circuits $= \frac{450}{3} =$ 150 K.V.A.

In Fig. 2·50.—$OA_3 = OB_3 = OC_3 = 2,200$ volts.

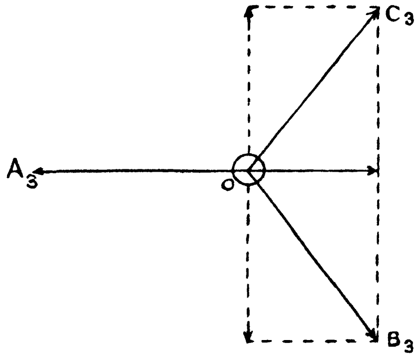


Fig 2·50

In Fig. 2·50.—$I_3' = I_3'' = I_3''' = \dfrac{1,50,000}{2,200} = 68·2$ amperes .

OA_3 —a to b externally or b to a internally.
OB_3 —b to e externally or e to b internally.
OC_3 —e to a externally or a to e internally.

Fig. 2·50 —Vectors showing how the internal E.M.Fs. of Fig. 2·51 combine to produce the external three-phase E M Fs. (b to e), (e to a) and (a to b).

Vectors of internal E. M. Fs. of the Scott-connection are shown in Fig. 2·51.

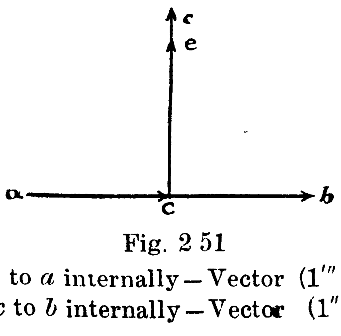


Fig. 2 51

I_a — c to a internally—Vector $(1'''_3 - I'_3)$
I_b — c to b internally—Vector $(1''_3 - I'_3)$

I_c — c to e internally — Vector $(I'''_3 + I''_3)$

I'_3 — a to b internally.

I''_3 — b to e internally.

I'''_3 — c to a internally.

Fig. 2·52.—Vector diagram of internal currents in the coils of Scott-connected secondaries of two-coil transformers like Fig. 2·47.

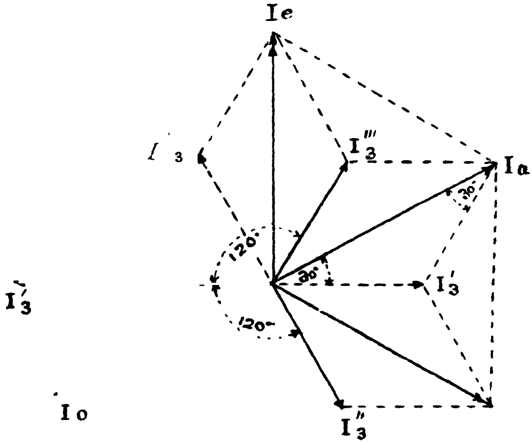


Fig. 2·52

From the relations developed in Fig. 2·52 we see that under the above conditions

$$I_a = I_b = I_c = \sqrt{3}\, I_3 = 1{\cdot}732 \times 68{\cdot}2 = 118{\cdot}2 \text{ amperes.}$$

Each of the two transformers must, therefore, have a capacity of 118·2 amperes at 220 volts, or 260 K. V. A. approximately and the total transformer capacity required is 2×260=520 K. V. A. in order to deliver 450 K. V. A. at the three-phase terminals.

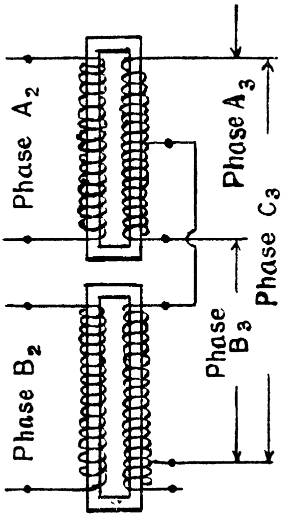


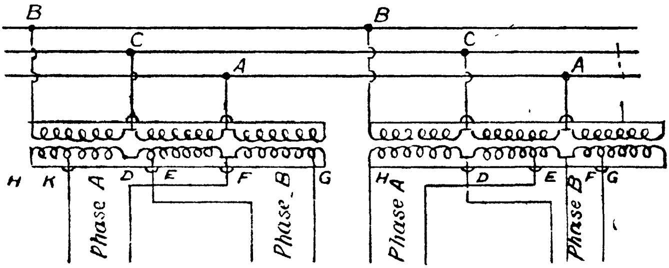
Fig. 2·53

Fig. 2·53 —Two transformers with primaries connected to two-phase line, and secondaries tapped and connected according to Scott system delivering three-phases (A_3, B_3, C_3). This scheme may be used with a three-wire two-phase line, which is impossible with autotransformers.

This problem applies only to two-coil transformers like Fig. 2·53, it does not apply to autotransformers connected according to the Scott system, as in Figs 2·47, 2·48 and 2·49.

If the power-factor of the three-phase circuit becomes less than unity, say 0·87, while the load remains balanced, it does not affect the transformer capacity required for a given K.V.A. output. The effect is merely that the vector relations of Fig. 2·50 remain exactly the same while the whole diagram of currents shifts around so that the currents I_3', I_3'' and I_3''' make angles of 30° (=arc *cos* 0·87) with the respectively corresponding E.M.F. vectors OA_3 OB_3 and OC_3 of Fig. 2·50.

It is to be noticed that in the transformer AB (Fig. 2·53), the part ac carries a current leading the E.M.F. in this part by 30° (see Fig 2·52), while the part cb carries a current lagging behind the E.M.F. in this part by 30°. This not only has the effect to require total transformer capacity in excess of the actual load delivered, as shown above, but also affects the voltage regulation of the transformers, and the balance of voltages in the phases. By comparing Fig. 2·50 with Fig 2·52 we see that the phase relation of current to E.M.F. within the coil ce is exactly the same as the phase relation of I_3'' to OB_3, or of I_3''' to OC_3; that is, when the external load is non-inductive the current in ce is in phase with the E.M.F. in ce.



Taylor-connection 3-phase to 2-phase with 3 Transformers.
Fig. 2·54

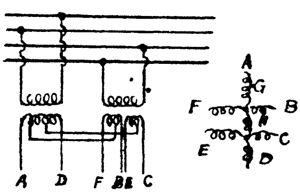
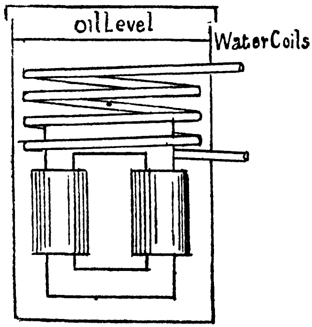


Diagram Showing Phase Relations Two-Phase to Six-Phase Transformation.
Fig. 2·55

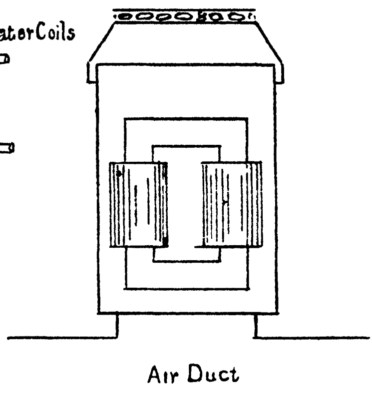
53. Maximum rise in temperature.—The windings shall not increase in temperature more than 50°C as measured by resistance above the surrounding air, and the other parts shall not increase more than 50°C, as measured by thermometer.

54 Means of Dissipating Heat—(1) Provide sufficient surface in the subdivided transformer to transfer the heat to the cooling agent, air or oil, without too great a difference in temperature ; (2) so subdivide the transformer that no part of the iron is more than one inch, and no part of the copper more than 3/8 inch, from a cooling surface ; (3) provide a sufficient quantity of the cooling agent, air, oil or water to carry away the heat at the same rate as it is generated ; and (4) provide sufficient surface on the containing case or tank to transfer the heat from the internal oil to the external air without too great a difference in temperature.

Cooling of Transformers



Water-Cooled Transformer.
Fig. 2'56



Air-Blast Transformer
Fig 2'57

55. Methods of Cooling :—Transformers may be divided into three general classes, depending upon the method of cooling, *viz.*, air-blast, oil-immersed self-cooled, and oil-immersed water-cooled. **Air-blast transformers** depend upon a forced circulation of air over the surface of the core and coils to carry away the heat. They may

be built for large capacities, but the voltage rarely exceeds 30,000, because of the difficulty of insulating them properly.

Oil-immersed self-cooled or water-cooled transformers are generally used with hydro-electric power developments, the latter in the generating station, while either type may be used with the sub-station depending upon the availability of cooling water. Both types are built for the largest capacities and the highest voltages self-cooled oil-immersed transformers have the core and coils immersed in a tank of oil, the tank usually being corrugated so as to increase the surface available for dissipating the heat generated in the core and coils. By the addition of external radiators, it is possible to greatly increase the cooling properties of the transformers, and the use of these radiators now make it possible to build self-cooled units for very large capacities. Water-cooled oil-immersed transformers depend upon the circulation of water through a coil placed in the top of the tank to carry away the heat from the oil. With about $\frac{1}{3}$ gallon of water per minute per kW. loss, the rise in temperature of the outgoing over the incoming water will be about 10°*C*.

Protection against heat can readily be obtained by providing sunshades, and in certain instances very good results have been obtained by simply painting the tanks white or light gray.

56. Cooling Water :—Artificially-cooled transformers never run continuously even at no-load, unless the cooling medium is first in operation. It is essential, therefore, to maintain a proper circulation in the cooling system.

If for any reason the water circulation is stopped, the load is immediately reduced as much as possible and close attention is given towards the temperature. If the oil at the top near the centre of the tank reaches 80°*C*, the transformer is cut out of service at once. The temperature is recognised as an absolute limit and is not allowed to exceed under any circumstances. This high temperature 80°*C* is allowed in any emergency

period and then only for a short duration. The temperature of the ingoing (cooling) water is always about 25°C.

57. Cooling Coils : - Nearly all the cooling water will, in time, cause scale or sediment in the cooling coils. But the time required to close up the coils depends upon the nature and condition of the cooling water. Any clogging in the coils decreases the efficiency in the cooling system and will be indicated by the high-oil temperature and a decreased flow of water, when the load condition and the water pressure remain constant. If cooling pipes are made of iron, the most frequent cause for clogging is the presence of oil in the water, which results in the formation of a scaly oxide

58. Scaling the Coils : —Every sort of scale or sediment that forms in the cooling coils should be removed from time to time without removing the coils from the tank. To effect this both the inlet and the outlet pipes are disconnected from the water supply and temporary piping installed to a point some feet away from the transformer where the coils can be emptied and filled safely. While doing this, special care should be taken so that no dust or acid enters into the transformer.

All the water in the cooling coils is drained and blown out. It is then filled with a solution of hydrochloric or muriatic acid of a specific gravity 1·01 equal quantities of commercially pure hydrochloric acid and water gave this sq gr. of 1·01). This solution is then forced into the cooling coils by partially restricting one end of the coil so that the solution will not be washed when it is full. After the solution has stood for about an hour in the coil, the coil is then flushed out thoroughly with clean water. If all the scale is not removed the first time, the operation is repeated until the coil is clean using new solution each time. The number of times it is necessary to repeat this process depends on the condition of the coil, and the water used for the cooling purpose. The chemical action which takes place is very violent and often forces out the acid sediment, etc., from both ends of the coil. Such deposits decrease the efficiency of the coils and are, therefore, thoroughly cleaned This condition of the coils is indicated by a higher oil temperature

for a given flow of water and load condition. The coils are examined and cleaned whenever signs of this type are found. This sort of trouble of clogging occurs only where iron pipes are used for cooling

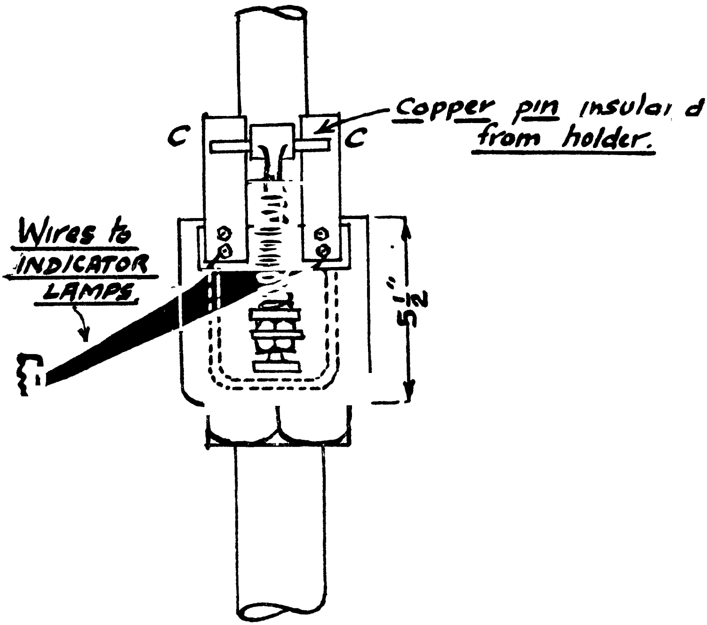
59 Copper-Cooling Coils :—All the transformers in Sivasamudrum were having iron cooling coils, but ever since this trouble of clogging began to occur often, they have been replaced by copper-cooling coils. These do not clog so readily as iron coils, when they do so the treatment specified above for iron coils are adapted. The coils are thoroughly blown out before treating with acid and all the sediment or scale is removed.

60. Idle-Cooling Coils :—When the water-cooled transformers are idle and exposed to freezing temperatures, the water in the coils is completely removed and, if possible, the coils are dried out by hot air. If not, they are filled with oil for the time

61. Drainage of Cooling Coils :—If both ends of the cooling coil project out through the. cover of the transformer, it is impossible to clean and drain out the coils in any case. It is for this reason that in some transformers one coil is brought at the top and the other near the bottom or at times both are brought out through the tank near the bottom. The water is removed by blowing compressed air at a suitable pressure.

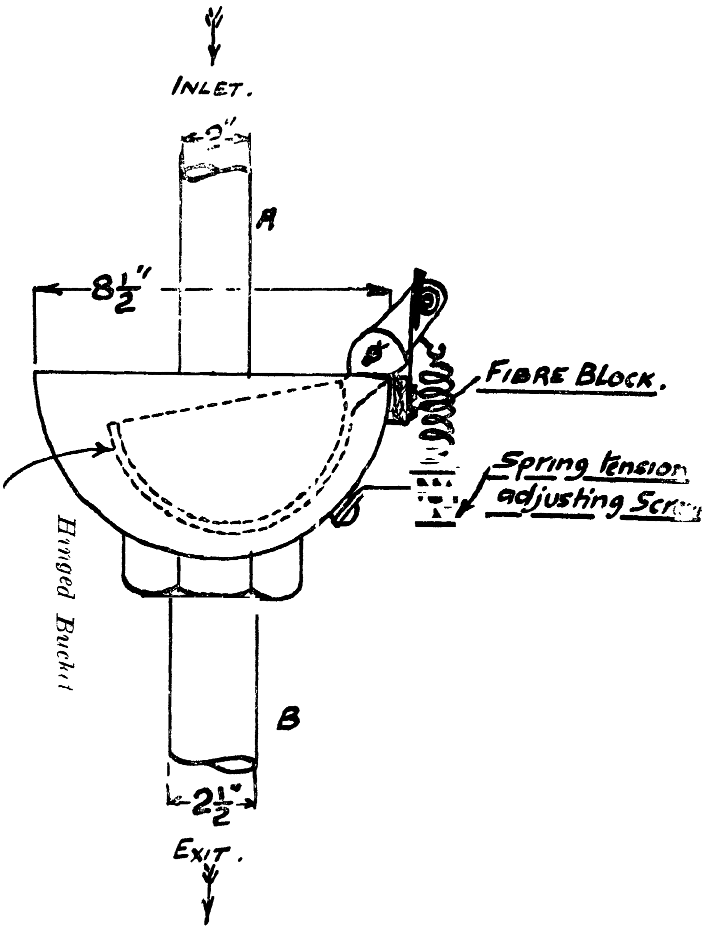
62. Temperature Indicator :—Two banks of the transformers of oil-immersed and water-cooled are provided with alternating current type of temperature indicator. With this type of temperature indicator, actual temperature of the transformer winding, while the load is on the transformer, can be determined.

The thermal elements consist of non-inductive exploring coil wound among the turns of the transformer windings and are so arranged that they always closely follow the temperature of the transformer. This exploring coil, connected through a suitable current transformer, forms one leg of a Wheatston bridge. The rest of the bridge is so designed that changes in temperature of the exploring coil will effect the balance of the bridge in a predetermined manner and permit the reading of the


Copper pin insula d
from holder.
C
C
Wires to
INDICATOR
LAMPS
5½"

Water Relay.

To face page 109



Water Relay

indicating meter, being calibrated accurately in centigrade scale. One meter with its auxiliary apparatus is used to indicate the temperature of 3 single-phase transformers, each transformer being equipped with an exploring coil.

63. The Water-Relay.—The circulation of the cooling water in the transformers must be continuous when they are in service. If, by any reason, the circulation stops, the transformers may get dangerously heated up and may get burnt even. In order to enable the switch-board attendant to know at a glance the condition of the water circulation in the transformers placed downstairs, what are called "Water-Relays" are used.

The principle of operation is as follows:—The water after circulating through the transformers is made to pass through the water-relay before going to the sump Each transformer is provided with one water-relay. There is a hinged bucket having a hole in the middle. So long as the water circulation is going on, the water coming down by the pipe pours over the hinged bucket and by its weight pulls the bucket down and a lever connected with the bucket closes the circuit of a lamp placed at the top of the switch-board. If the water supply stops, the bucket, being no longer pressed down, is pulled up by a spring and the contact is broken, thus putting out the light on the switch-board.

The transformer is thoroughly cleaned by blowing out air and all particles of foreign matter are removed. If the coils and insulation are very dirty, they are at times washed with dry transformer oil at a pressure of 25 to 50 lbs./in^2, which is easily obtained by the pump of the oil filter and drier outfit. All valves, drain cocks, plugs and oil gauge openings are thoroughly cleaned out as also fitting themselves before being assembled on the transformer tank. The fittings are securely screwed home with proper jointing material, *i.e.*, boiled oil and red lead as leakages, after transformers are installed, are annoying and expensive to stop. The tank is then thoroughly cleaned out and every trace of dirt or moisture removed. Care is taken that clothes used in

cleaning the transformer tank are not such that loose fibres can readily be detached Fibrous material left on the surface of the tank or transformer will eventually be held in suspension in the oil and possibly decrease the insulation properties to a great extent.

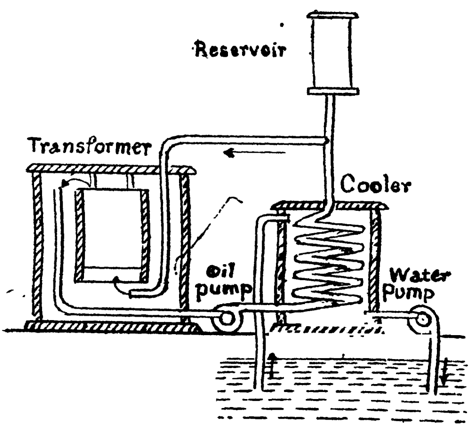
64. Other methods of cooling.

(a) **By natural convection of air and radiation** :– Used in small distributing transformers up to 25 K. V A., such as instrument and small switch board transformers

(b) **By natural convection and radiation with two fluids** :—Oil-insulated air-cooled transformers are cooled in this manner. This method may be applied to transformers for all voltages and for ratings up to 4,000 K. V. A.

(c) **By a combinaton of natural convection of a fluid medium with forced convection of cooling air** :—This method has not been much used in America but is in great favour in Europe.

(d) **By natural convection of an insulating fluid** which is to be cooled artificially by another fluid. This method is used in oil insulated water-cooled transformers. The cooling coils are suspended in the tank in the oil near the top, usually above the transformer, and carry a continually circulating stream of water.



Transformer Cooled by Circulating oil.
Fig 2·58

(e) **By forced convection of an insulating**

fluid which may be cooled in any convenient way. This method has been employed to cool large transformers by forcing the cooled fluid through the windings.

Forced oil circulation with the oil cooled by air-blast may be employed in one self-contained unit.

65. Drying Out :—Although a transformer is made as nearly waterproof as possible, but after transit over long distance it is considered safe to dry it out first and then it is put in service. All the transformers for 10,000 volts and above, whatever the size they may be, are dried out unless they are shipped from the works in a sealed transformer tank with oil covering the windings. The insulation resistance between high tension side and ground and the I. R. drop are measured several times during the heating process.

66. Test for Moisture :—High insulation resistance, as measured by an ohmmeter with the transformer cold, is no criterion for dryness. A damp transformer may show high resistance between its winding and core when cold, but in course of drying out this will fall. The transformer will not be dry until the insulation resistance has been raised. No general rule can be given as to the time taken to dry out a damp transformer. The condition of the oil must be ascertained by test pressure, and the sample chosen must be drawn off from the bottom of the tank. In the case of transformers, with forced oil circulation, see that the pressure of the oil is greater than that of the water in the cooler ; so that should any leakage occur, the oil will be forced out and water prevented from entering.

For any reason, an interruption occurs in the circulation of the cooling medium, the temperature of transformer must, on no account, be allowed to exceed 90°*C*. If there is any danger of this temperature being exceeded, the transformer must be cut out of circuit ; for, if allowed to run longer, the windings may be permanently damaged.

67. Drying of Core and Coils :—The drying of a transformer core and coils is done in so many ways, but the method employed depends upon the availability of

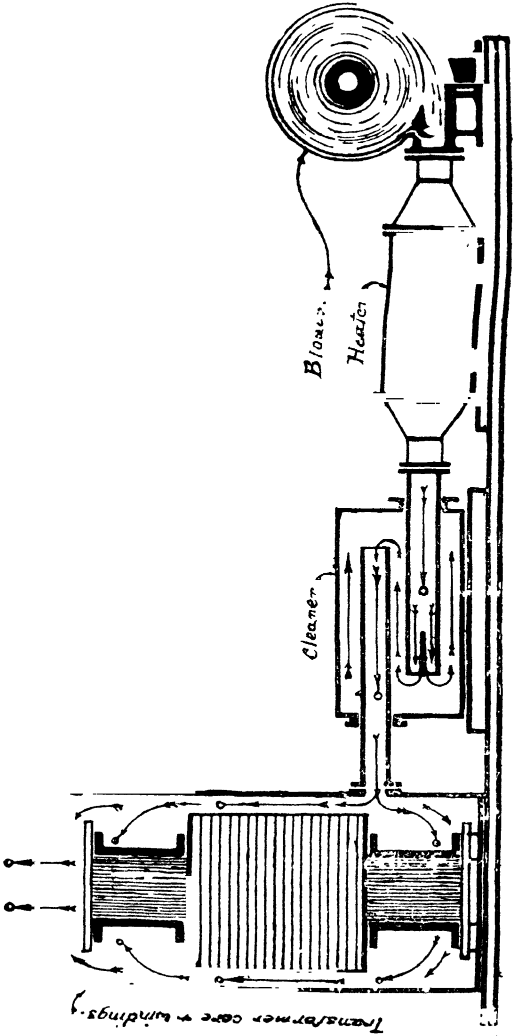
the apparatus required. The methods employed are as follows:—

(1) Drying room method with calcium chloride.
(2) Forced air method.
(3) Natural draught method.
(4) Short-circuited method of drying.
(5) Short-circuit and vacuum process.
(6) Drying out by oil-immersed resistance.

(1) ***Drying Room*** *:—This method is employed when* a suitable oven is available; drying is most conveniently done by placing the transformer in the oven at a temperature not exceeding 85°*C*. A tray with calcium chloride in the oven room will greatly facilitate the drying process. About 10 lbs. per 1,000 K. V. A. rating is generally required. When calcium chloride is not available, dry lime is used but 3 or 4 times the quantity.

(2) Forced air method :— One of the best methods of drying is by forcing dry air at a temperature of 85°*C* into the coils at the bottom of the transformer allowing the air to escape at the top. The volume of air used should be such that the temperature of the escaping air is approximately the same as the surrounding temperature. Various pipes and deflectors are used so that the draught of hot air will reach all parts of the winding.

Caution :— Oil is not allowed to run from the transformer into the heater as it will cause a serious fire. In order to eliminate the risk of fire a baffle is placed in the pipe line between the heater and the transformer; so that if for any reason trouble occurs in the latter, sparks will not reach the transformer. This baffle is made from a section of sheet iron pipe covered with asbestos. The following tables are supplied for information for the quantity of air to be supplied for different sizes of transformers.

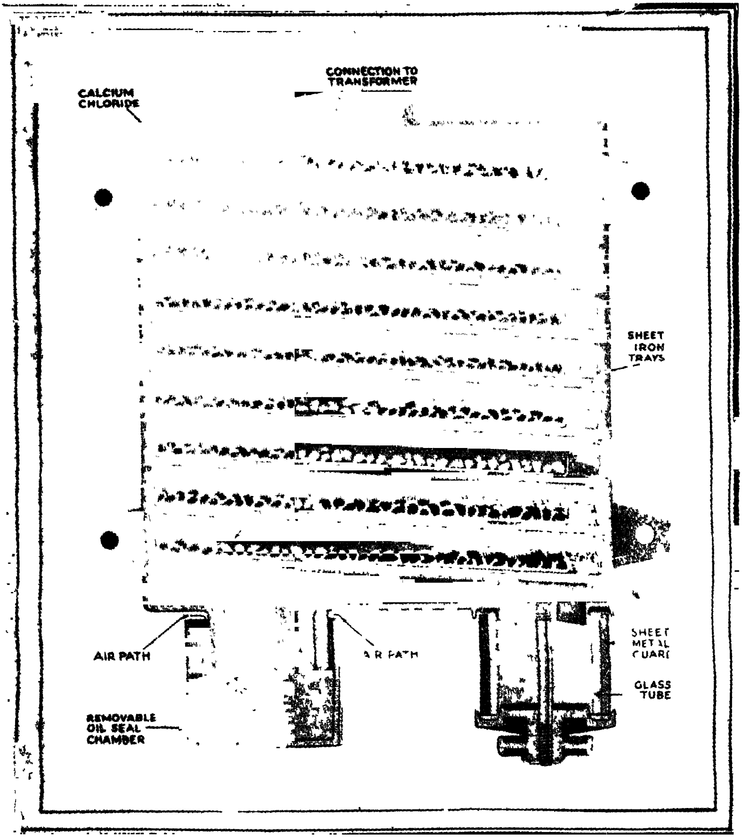


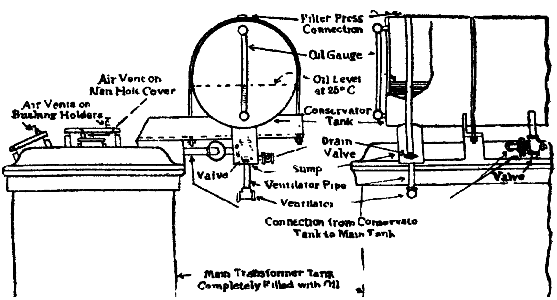
Forced air method of drying
Fig. 2·59

Dia. of tank in inches.	Equivalent area of tank.	Air per min. in cubic feet.
54-72	2290-4072	600
78-96	4778-7238	900
102-120	8170-11330	1200
126-144	121480-16280	1500
150-168	17700-22180	1800

(3) **Natural draught method of drying :**—In some urgent emergency cases, when a blower is not available, this method is used. The transformer is dried by external heat, allowing the hot air to circulate by natural draught. The source of heat being resistance of grids. These are run at a low temperature to avoid the risk of fire and are never placed directly under the transformer where oil might drip on them and thus be ignited. The grids are placed in a suitable box of fire-proof materials, a short distance away, and the hot air led to the transformer by a pipe. The transformer is boxed in, so that the boxing will act as a flue to maintain the draught. Dampers are provided in the heat box to regulate the flow of air. Thermometers are so placed as to indicate the temperature in the pipe line between the heater and the transformer and also the out-going air. The ingoing temperature is kept about 80° to 85° *C.* To ensure uniform heating the quantity of heated air is so regulated that the outgoing temperature is not noticeably lower than that of the ingoing air. Usually it takes about 15-20 kW. to dry a transformer of about 2,000 K. V. A capacity.

(4) **Drying by short-circuit method.**—This method can be employed with the transformer either in or out of the tank. Short-circuit the *L. T.* windings and if the *D. C* supply is the only source, connect the *H. T.* windings in series and have a regulating resistance in circuit to control the temperature rise. However, if an *A. C.* voltage is available equal to from 1 % to 5 % of the normal *H. T.* voltage, it is


CONNECTION TO TRANSFORMER
CALCIUM CHLORIDE
SHEET IRON TRAYS
AIR PATH
SHEET METAL GUARD
GLASS TUBE
REMOVABLE OIL SEAL CHAMBER


Filter Press Connection
Oil Gauge
Oil Level at 25° C
Air Vent on Man Hole Cover
Air Vents on Bushing Holders
Conservator Tank
Drain Valve
Sump
Valve
Ventilator Pipe
Ventilator
Valve
Connection from Conservator Tank to Main Tank
Main Transformer Tank Completely Filled with Oil

preferable to use this source of power The current varies with the size of the transformer, and must be sufficient to raise the temperature of the transformer to between 80° *C.* and 90° *C.*; and it will be found to be in the neighbourhood of from 15 % to 20 % of the normal full-load current for transformers of 1,000 K. V. A. and over. For the smaller transformers the current will be proportionately greater. If the impedance voltage be multiplied by this percentage current, it will give the percentage of full-line volts required. When only a single-phase supply is available, connect the winding in series, and 1·73 times this calculated value is required if the transformer be normally connected in star, or three times its value, if it is connected in delta. If it is desired to apply voltage to the *L. T* side and have the *H. T.* shorted, special care should be taken that the short circuit is substantial, as a dangerous pressure may be induced in the windings if the short is accidentally broken whilst the current is flowing The temperature should be measured by a *thermometer* as well *as by the resistance of the winding*. In using mercury thermometers care must be taken not to break them, as otherwise mercury may become lodged in the windings. Also they should be placed outside the influence of magnetic leakage fields, as otherwise *eddy currents* will be produced in the *Hg* and the thermometer will give higher temperature. If *A. C.* is being used for heating, the supply must be temporarily interrupted whilst the resistance of the windings is taken by means of *D. C.* and the temperature determined by means of the following formula :—

$$T. = \frac{R_h \, (234{\cdot}5 + T_c) - 234{\cdot}5\, R_c}{R_c}$$

where, $T.$ = Temperature of hot winding,

T_c = Temperature of cold winding,

R_h = Resistance of hot winding,

and R_c = Resistance of cold winding.

The drying out will take anything from 8 to 36 hours, depending on the state of the windings and the exposure they have received. If at any time the temperatnre exceeds $90°C$, the current must be switched off till it falls to $80°C$. If there is no intermediate adjustment on regulating rheostat, then the process of switching on and off the current at regular intervals may be pursued.

(5) **Short-circuit and vacuum process :**—When transformer is forced air-cooled and encased in a strong tank with an airtight lid, this method may be adopted and it is similar in principle to that of drying the oil under vacuum. A vacuum of 25″ is usually employed and the process dries the transformer at a low temperature thus eliminating the risk of damaging the insulation through overheating The windings may be connected in a similar manner to that stated above, but obviously a lower current and voltage (if $A. C$) will be required to produce the lower temperature. As before, the operation is continued till the insulation curve commences to rise. If the transformer has not been dried immersed in oil, admitting the oil to the tank whilst under vacuum after the drying out is completed, will prevent the formation of air bubbles in the interstices of the windings.

(6) **Drying out by Oil-immersed Resistance.**—Fill up the oil tanks with oil or spirits before assembling and when the transformer has been placed in the tank. Oil should always be put in the transformer through a filter cloth, and the level raised till it can be seen in the gauge glass or until it is just below the tops of the tubes in the case of tubular tanks Raise the cover off the transformer, but if this is not possible on account of its construction, it should be raised along with transformer until it is one foot above the top of the tank. This is to allow for the egress of moisture vapour. The heating coil should be placed as near the bottom of the tank as possible and symmetrically disposed. A suitable ammeter, voltmeter, switches, fuses and regulating resistance should be placed in the circuit. To curtail the power consumed the tank should be well-lagged on four

sides, and suitable place left for reading the oil temperature near the top of the tank. During the drying process the oil should be kept at a temperature of not more than 100°*C*. if high grade oil be used or 80°*C*. for ordinary oil. It is to be remembered that the limiting temperature will be in the vicinity of heating coils. Insulation resistance of *L. T.* to earth and *H. T.* to earth and *L. T.* to *H. T.* should be regularly taken and the result plotted on the time basis. Whilst the temperature is increasing, the resistance will gradually drop and when drying out process is nearing completion, it will commence to rise. If the heaters are then shut off and the transformer allowed to cool, the resistance will rise rapidly to a very much higher value If difficulty is experienced in obtaining this rising characteristic on the insulation curve, then allow the transformer to cool down once or twice to allow the residual moisture to diffuse in the oil and come into more intimate contact with it. Also it is a good plan to draw off some oil from the bottom of the tank at regular intervals and return it to the top as this will assist matters in the same direction.

NOTE :—*Under no consideration must a transformer, which is being dried out, be left without attention.*

68. Breather :—It is advisable to have the transformer-covers tight-fitting to prevent entrance of moisture. This is effectively accomplished by placing a gasket between the tank and cover. Weather-proof ventilators, to prevent trapping of moisture within the tank, are essential, however, especially with large power transformers. The variation in volume of the air and oil in transformer tanks, due to the variation in the temperature of the transformer itself or that of the surrounding air, produces a constant breathing or interchange of air in the top of the tank and the surrounding atmosphere. This breathing may result in danger to the transformer because of the lowering of the temperature of the enclosed air to the dew point, which results in condensation of water vapour within the tank. The gradual accumulation of minute quantities of moisture will greatly decrease the

settle to the bottom. The time required for the moisture to settle depends upon the size of the container and temperature, and may require several days in the case of coil oil in large transformers.

It is recommended that one quart of oil be taken as sample. If the oil is in air-tight drums, it will be satisfactory to take one composite sample from each five drums. If there is any doubt regarding the quality of oil, however, test samples from each individual drum, especially, if, when first loosening the bungs no hissing sound is heard. The hissing sounds evidence that the drum is air-tight. There is practically no possibility of moisture entering cans which are hermetically sealed and unless cans appear to be leaky there is no need to make dielectric tests.

To take samples which are fairly representatives of oil in the bottom of the tank, draw off sufficient oil to ensure that the sample will not be of that oil stored in the sampling pipe.

A large glass receptacle is recommended for the sample, so if water is present it may be readily observed. If water is found, investigate the cause and apply a remedy.

Store all sampling apparatus in a dry clean cabinet. Keep containers for samples closed. After filling close the tops immediately.

(If no facilities are available for making dielectric tests, send samples to the nearest testing office)

Testing :—Test the sample between polished brass or copper disk electrodes one inch in diameter and having square edges. The electrodes should be placed with their axes horizontal and coincident with 0·1″ gap between their adjacent faces.

Wipe the containing vessel and electrodes, clean and rinse thoroughly with oil free dry gasoline, until they are entirely free from fibres Then rinse at least once with the sample of oil to be tested The temperature of the gap should be between 20° and 30°C (68° and 86°F). Gently agitate the sample before each filling of the testing vessel to prevent variation in results due to settling in the sample container. Fill the gap with the oil to a height

not less than 200 mm above the top of the discs. Pour the oil gently into the receptacle so that no air bubbles are formed. If the oil has been allowed to squirt out crackling a large valve, let it stand for 15 minutes before testing.

Apply voltage and increase uniformly at a rate of about 3,000 volts per second until break-down occurs as indicated by a continuous discharge across the gap (occasional momentary discharges which do not result in permanent arc may occur; these should be disregarded.)

Provide for opening the primary circuit as quickly as possible after break-down has occurred in order to prevent unnecessary carbonisation of the oil After each puncture, jar the testing vessel to loosen particles of carbon adhering to the electrodes and gently agitate the oil but not with sufficient violence to introduce air bubbles. Make five break-downs on each filling, after which empty the vessel and refill with fresh oil from the original sample. Continue the test until the mean of the averages of at least three fillings are consistent within 10 %.

The standard dielectric strength of oil when shipped is at least 22 K. V with one inch discs placed 0·1 apart. If the dielectric strength of the above oil in service becomes less than 75 % of the above value think that it requires drying. Do not put new oil of less than the standard dielectric strength to a transformer.

Drying Oil and Filling Transformer

Drying and filtering oil.—Oil, whether shipped in sealed drums or in special tank cars direct from the manufacturer, may require drying at its destination before it is suitable for use in high voltage transformers. Therefore, test the oil according to the instructions under " Sampling and testing oil and bring the dielectric strength up to at least 22 K V. before using. If it is absolutely necessary to use a part of the oil from the drums before tests can be made, allow the oil in the drums to settle for several hours and then pump from the top to within about 4″ from the bottom; that is, do not use oil which settled to the bottom until it can

be tested and, if necessary, dried. The oil is treated in a filter press by being forced through several layers of blotting paper which removes all moisture and solid matter held in suspension in the oil By this method from 350-1200 gallons of oil, according to the size of the press, can be treated in an hour.

Filling Transformer :—Before filling the transformer with oil make sure that all accessories are fitted with oil-tight joints. To do this fill the threads with bakelite varnish. Use metal hose rather than rubber hose, as transformer oil dissolves the sulphur from the rubber, and the sulphur attacks the copper in the windings. In order to prevent aeration of the oil it is preferable to fill the transformers through the bottom drain valve by means of a filter press.

Connections for filling Transformers with Oil

When the oil tests satisfactorily and is not run through a filter press, stress it through two or more thickness of muslin or other closely-woven cotton cloth.

Renew the straining cloth as often as necessary, at least one set of cloth for each transformer.

Filter press operation :—Any free water must be removed before or during the drying by draining, as ten filter press treatment removes only water, that is, held in suspension in the oil.

The drying may be slightly hastened by periodically filtering the oil ; while the run progresses, continued filtering may keep the oil temperature down to an effective value. It is better to filter only a few hours each day. Usually drying will progress satisfactorily with little filtering if thorough ventilation is provided.

By the short-circuit method, the oil may be filtered at the same time without danger from coil break-down, with the comparaitively low voltage used for drying. Air in the oil is, however, detrimental. Take care to prevent it.

Temperatures :—As pointed out, it is desirable to maintain top oil temperature up to the limit with load continuously applied. See that the thermometers used

are in good condition and the top oil temperatures are accurately observed. Spirit thermometers only should be used in the oil when checking reading of dial thermometers

Oil Tests :—If the oil either at the top or at the bottom of the tank tests less than 22 K V. before starting the short-circuit run, filter it. Take oil sample every four hours from both the top and bottom of each transformer and test them. Have an oil testing outfit all the time. A 3 kW. 30 K. V. induction regulator operated outfit is the best. The top samples should be taken from the centre manhole opening. The bottom samples may be obtained from the cock in the drain valve.

From the records plot a curve of the oil tests top oil temperatures and the load current (against time) as this curve will progress of the drying.

When to Discontinue Drying :—While moisture is being given off, the top oil samples may test lower than the bottom samples.

When the winding and insulation are dry, the oil begins to increase in dielectric strength and it is not uncommon to have it reached 30 K. V. or more at the top and bottom.

Continue the drying until the oil from top and bottom tests 22 K V preferably 30 K. V or higher between 1 0 inch discs placed 0·1 inch apart for seven successive tests taken four hours apart with the oil maintained at a maximum temperature for the load held and without filtering. A decrease in the dielectric strength of the oil indicates that moisture is still passing from the transformer into the oil

Unless constant, or preferably increasing dielectric strength is shown by these tests, indicating that drying is complete, continue the drying process.

After completion of the drying run, be sure that the oil added to fill the tank completely is well filtered and of high test value. The hot oil is free from oil bubbles, so it is preferable to complete filling the transformer from the top of the tank or conservator rather than the drain valve, as in the latter case air bubbles may be trapped in the winding.

After the drying is discontinued and the tank and conservator filled with good oil, operate the transformer for 24 hours at approximately 2/3 the voltage (no-load), while at a high oil temperature, make similar tests of oil samples and filter, if necessary (Obtain top oil samples from one of the air vents on conservator type tanks). After satisfactorily making the two-thirds voltage test, apply full voltage (no-load) for 24 hours and make the same tests. Water-cooled transformers may require some water to hold the top oil temperature within the 85°*C* limit on this test.

Normal Operation Method :—This method depends on freeing the transformer from moisture while in service partially by filtration, but mainly by forced or mutual ventilation, and is applicable only to open type transformers

Open type transformers in service, which show moisture condensation but which cannot be shut down to apply the short-circuit method, may be dried as follows, though there is an element of risk involved.

Heavily lag the main cover except one manhole. Ventilate as described under "short-circuit method" or add a funnel with a cheese cloth screen to a small opening such as one of the breathing openings in an open type transformer, placing a desk fan to flow directly into it, and provide a second protected opening for the air to get out.

Inspect the manhole door frequently and raise oil temperatures by blanketing the tank or increasing the load If condensation appears on the under side of the manhole cover reduce the oil temperature and run until the moisture disappears. Then raise the temperature again by 10°*C* steps.

If at any time the oil at top or bottom of the main tank tests less than 16·5 K.V., operate the filter press and bring the oil up to 22· K. V. test.

Continue the drying for 3 days after reaching the maximum oil temperature in accordance with the following table :—

Amp. in percentage of f. L.		Maximum top oil temperature in °*C*.
Self-cooled transformers.	Water-cooled transformers.	
50	50	85
85	75	75
100	85	70

If no condensation is then found, see instructions under "When to discontinue drying."

Insulation Resistance and Meggar Readings :— Meggar readings cannot be relied upon to indicate the progress of drying in transformers which are filled with oil. Since in this case the resistance of the oil is measured in parallel with that of the solid insulation resistance of a transformer without oil, as determined by meggar readings, cannot be relied upon as a sure indication of its condition at any one time. The general trend of the readings as a drying run proceeds, is a fairly accurate indication of the progress of drying. Continue the drying process until the readings become approximately constant at a value considerably above the low readings. Variation in temperature causes wide variation in resistance, the values varying inversely with each other.

If the meggar shows a short circuit, *i.e.*, an insulation resistance too low to be read, it is very likely due to an excessive amount of moisture. Low readings also sometimes indicate the presence of moist spots in the insulation. Widely different meggar readings may be obtained

from different transformers; but the average readings should be approximately alike for transformers of the same capacity and design.

71. Placing in Service :-It is recommended that a short-circuit run of about 2 hours be made on every transformer of 60 K. V. and above before putting on full excitation. This is for the purpose of releasing any bubbles of air which might be tapped in the windings when filling the transformer with oil and might lead to corona discharge and even to failure If the coil is cold from 100-125 % load current may be used The required voltage may be calculated as in a drying transformer.

72. Operation :—Before putting a new transform er, which has been withdrawn from the oil, or which has been filled up with new oil, into commission it should be run for a few hours on short-circuit at approximate full-load current to drive out air bubbles from the windings. When applying the line voltage for the first time, the pressure should be brought up gradually and *the transformer allowed to remain on open circuit for sometime.* Before taking load from a water-cooled transformer and where one cooler serves several transformers, see that the oil is being equally shared by all transformers and make sure the correct quantity of oil and water is flowing through the cooler. If a slow increase in temperature is observed during the normal working of the transformer, note whether scale is being formed in the cooling tubes. In all cases, as soon as the temperature 90° C is reached, the transformer should be cut out of service

73. Inspections :—The insulation resistance of the windings should be periodically taken. Every six month a sample of the oil should be drawn from the bottom of the tank and tested. If moisture is found to be present. the transformer oil should be dried by one of the methods mentioned The windings should be examined and freed of any sludge or deposit. Where automatically adjusting coil supports are not provided, the shrinkage of the windings should be taken up by re-adjusting the coil supports. Also the core bolts may require tightening

up. The terminals will require cleaning and porcelains inspecting for cracks. Scale may be removed from cooling tubes by employing a weak solution of hydrochloric acid of strength about 8 %, one carb. of acid being mixed with three of water One carb. of mixture will do for 400 sq. ft. of tube surface and the solution of the scale will be completed in about 20 minutes.

74. Single *versus* group of Transformers in Polyphase System – For smaller sizes up to about 200 kW. the ADVANTAGES of the three-phase transformer over a group of three single-phase transformers of the same total capacity, efficiency, temperature rise and regulation are :—

(1) Lower cost.

(2) Requires less floor space.

(3) Has less weight.

(4) Connections and outside wiring very much simplified, as only three primary and three secondary leads are usually brought out.

(5) Lower transportation charges and cost of installation.

(6) Presents a symmetrical and compact appearance

The DISADVANTAGES of the three-phase type are :—

(1) Greater cost of spare units.

(2) Greater derangement of service in case of break-down.

(3) Greater cost of repairs.

(4) Reduced capacity obtainable in self-cooling units.

(5) Greater difficulty in bringing out taps for a large number of voltages

For *very large transformers*, on the other hand, the cost is lower in the case of three single-phase transformers. (The weight is as before greater than that of a three-phase transformer).

Generally, a three-phase transformer has the advantage over three single-phase transformers of maintaining better balance of the P. D. on the three phases, owing to the interlinking of the magnetic circuit.

In general single-phase transformers are preferable where only one transformer is installed and where the expense of a spare transformer would not be warranted. In such installations the burn-out of one phase unit would cause considerable inconvenience for the reason that the whole transformer would have to be disconnected from the circuit before repairs could be made. If, however, single-phase transformers are used, one transformer can be cut out with a minimum amount of trouble, and the other two transformers can be operated at normal temperature, open Δ- or V-) connected at 58 per cent. of the normal capacity of the group of three transformers, until the third unit can be replaced.

With a three-phase shell-type transformer, if both the primary and the secondary are Δ-connected, trouble in one phase will not prevent the use of the other two phases in open delta By short-circuiting both primary and secondary of the defective phase and cutting it out of circuit, the magnetic flux in that section is entirely neutralized. This cannot be done, however, with any of Δ-connected transformers Where a large number of three-phase transformers can be used, it is generally advisable to install three-phase units.

75 Precautions in making connections of Transformers : - In the case of newly-installed transformers see that :—

(*i*) All the internal and external connections are properly done

(*ii*) The switching apparatus is in good working order.

(*iii*) If required to run in parallel, the transformers have all the same polarity.

Transformers of the same make may have the same polarity if similarly connected up, but still it is best to test for it. (See Phasing of Transformers, p. 77, etc.)

76. Autotransformer :—It is a transformer with one winding only; part of the winding of this being common to both the primary and secondary circuits. It

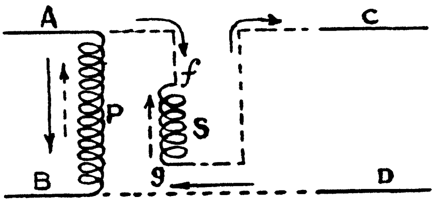
is so connected that part of the load current is supplied by the primary current ; and part by the secondary current. The relative amount supplied by each will depend upon the ratio of transformation. If the ratio of transformation is large, the current in the secondary will be large compared with that in the primary, and the proportion of the load current contributed by the primary current will be small If, on the other hand, the ratio of transformation approaches unity, the primary current will be large compared with the secondary current, and, therefore, the primary current will supply the greater portion of the load.

The primary voltage is the difference between the voltage of the supply circuit and that of the secondary circuit. The load current is supplied from the primary and the secondary in approximately inverse proportion to the respective number of turns in their windings.

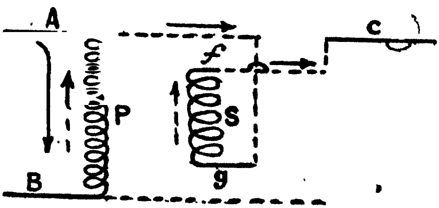
As the load on the secondary is increased, the primary voltage becomes greater so that the regulation of an autotransformer is very much better than when used as a simple transformer.

77. The Application of Autotransformer :— (1) It is used (*a*) to reduce, (*b*) to increase the primary pressure for the secondary circuit. In the latter case it is called Reversed Autotransformer.

(2) As starting compensators for motor starting work, or compensators as are



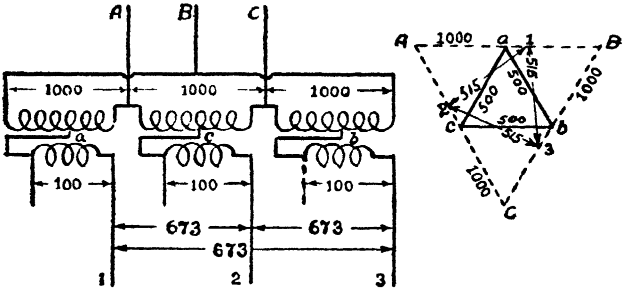
Connections for an Auto-step-up Transformer
Fig. 2·60



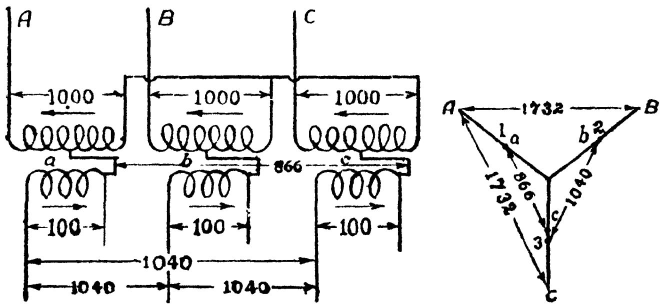
Connections for an Auto-step-down Transformer
Fig. 2·61

sometimes necessary in arc lamps or low voltage metal filament lamps, or to increase the primary pressure for the secondary circuit as used in series arc lamps.

Phase connections of Three-Phase Autotransformer :—



Three-phase △ Autotransformer connection.
Fig. 2·62



Three-phase Y Autotransformer connection.
Fig. 2·63

(3) When isolation of circuits is not very important, autotransformer is more useful as it has lesser size and cost. This is one reason why it is used as an economy coil.

(4) Used as a balancer in connection with rotary converters for supplying a three-wire direct current service.

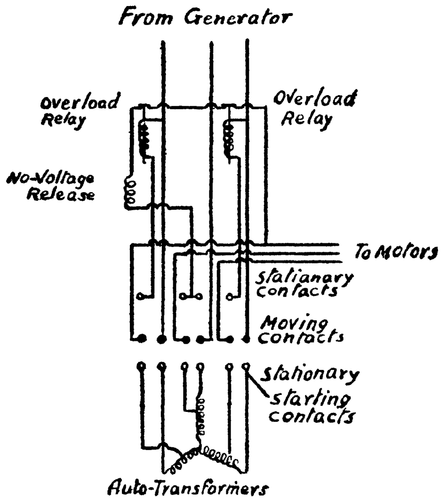
(5) Used for supplying a varying voltage to single-phase commutator motors and thus for controlling the speed of motors.

(6) Autotransformers are used as a means of interlocking two systems of different voltages. The three-phase autotransformers are commonly used for this purpose and these are star-connected and provided with delta-connected tertiaries for large ratios of transformation, and on high voltage work their use requires a grounded system for the sake of safety in operation.

78. Advantage of using Autotransformer as Compensator for starting motors:—The starting current taken by a squirrel cage induction motor at the instant of starting, is equal to the applied electro-motive force divided by the impedance of the motor. Only the duration of this current, and not its value, is affected by the torque against which the motor is required to start. In one case the motor is thrown directly, say on a 100-volt line The impedance of the motor is 5·77 ohms per phase, starting torque 10 lbs. at 1 ft. radius and the current taken 10 amps When a compensator is inserted, stepping down the line pressure from 100 to 50 volts, the starting current of the motor is reduced to one-half and the starting torque becomes one quarter its previous value or $2\frac{1}{2}$ lbs. at 1 ft. radius. The current in the line is reduced inversely as the ratio of transformation in the compensator, and becomes $2\frac{1}{2}$ amps.

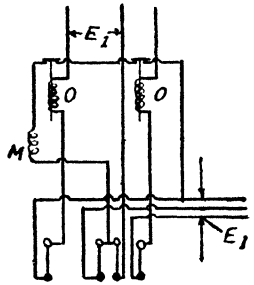
Thus when a compensator is used, the starting torque of the motor can be reduced to approximately the value required by the load, and the current taken from the line correspondingly decreased. Where a compensator is not used, an increase of rotor resistance results in a proportional increase in the starting torque of the motor with a very slight decrease in the starting current drawn from the line. Where a compensator is used with a motor having a high resistance rotor, the voltage can be reduced to a lower value than would be required with a

low-resistance rotor for the same starting torque. Standard compensators are provided with several taps from which various combinations can be obtained.



Complete Connections

Fig. 2 64



Running

Fig. 2'65

79. Disadvantage of Autotransformer :—The metallic connection between the primary and secondary circuits is a distinct disadvantage as it cannot be suitably used in high-voltage circuits.

Owing to such connection a dangerous shock may be given on the low pressure side in case of a breakdown. This can be prevented in ordinary transformers. The tertiary winding is often used to supply local power circuits and for synchronous condensers, by the use of an "EARTH SHIELD," which consists of a metallic sheet placed between the primary and the secondary circuit, and is connected to the core and thus to earth.

80 Limitation of Autotransformers:—They may be used for every purpose for which transformers are used but there is little to be gained by using them.

Rating of an Autotransformer:—The K. V. A. rating of an autotransformer does not refer to its output, but it gives an indication of its size, price and losses, as compared with that of a transformer for the output. In general, the rating of a single-phase autotransformer without taps may always be determined by multiplying the current in the high-tension line by the difference between the high- and low-tension voltages.

If, however, the autotransformer winding is complicated by taps, it is necessary to calculate the maximum current in each section of the winding and to multiply this current by the voltage of that particular section. One-half the sum of these products will be the rating of the autotransformer.

81 Economy of Autotransformer :—Let the two parts of the transformers have (1) cores of the same size, (2) the same flux density, and (3) the same transformation ratio The iron loss is the same in both, the voltage per turn will be the same, the total number of turns in the autotransformer the same as the primary of the two-coil transformer, and the number of turns in the secondaries is also equal.

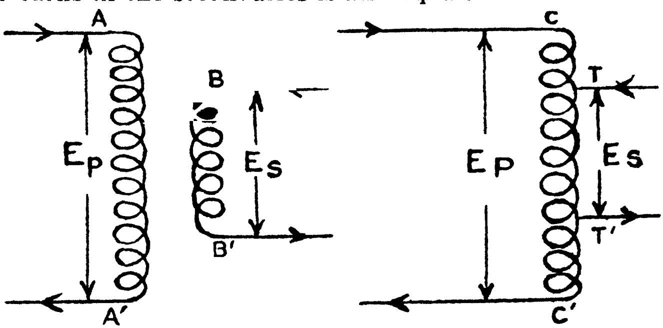


Fig. 2·66

Let T be the transformation ratio.

$$T = e_1/e_2 = n_1/n_2.$$

The number of turns in the parts of the autotransformer acting only as primary, CT and $T'C'$

$$=(1-1/T)\times n_1.$$

The currents carried by these being equal, the same cross-section of the wire is used.

The volume of copper in CT, $T'C'$

$$=(1-1/T)\times(\text{volume of copper in } AA') \quad \ldots \quad (1)$$

The current carried by TT' is the vector sum of I_1 and I_2. But as these are nearly opposite in phase, the vector sum is nearly equal to the arithmetical difference between the two, that is, I_2-I_1.

$\therefore$ If equal current densities are used, the ratio (cross-section of TT'/cross-section BB' of the secondary of the two-coil transformer)

$$=(I_2-I_1)/I_2=1-1/T.$$

The number of turns in these two are equal.

$\therefore$ volume of copper in TT'

$= (1-1/T)\times$(volume of copper in the secondary BB' of the two-coil transformer). ... ... (2)

$\therefore$ from (1) and (2), we get the total volume of copper in autotransformer

$=(1-1/T)\times$ (total volume of copper in two-coil transformer).

$\therefore$ saving is $1/T$ of the total (quantity of copper).

The copper losses in CT, $T'C'$ are similarly equal to $(1-1/T)$ of the losses in the primary AA'. The resistance of TT' is greater than that of the secondary BB' in the ratio $1/(1-1/T)$ owing to the smaller section of the former. But it carries only $(1-1/T)$ of the current in the secondary BB' of the two-coil transformer. Therefore, its I^2R loss is the same fraction of the loss in BB'.

$\therefore$ the total copper loss in the autotransformer

$=(1-1/T)\times$ total copper loss in the two-coil transformer.

The actual saving is of copper and the reduction in copper losses would be somewhat greater owing to some diminution in the length of the mean turn.

Instead of confining the saving to the copper, it is better to reduce the iron and the iron losses and save less copper. Autotransformer should be so designed as a two-coil transformer of primary *P. D.* equal to $(V_1 - V_2)$ and of secondary current equal to $(I_2 - I_1)$; its cost therefore is the same as that of a transformer of an output equal to $(1 - 1/T)$ of the actual output.

Example 17. Let an autotransformer have 20 turns.

Impressed voltage between the terminals $cc' = 200$.

$\therefore$ the fall of potential per turn of wire $= 10$ volts.

I, the current in it, $= 10$ amperes.

Let it be tapped at T and T', *i.e.*, having 10 turns between T and T'.

$\therefore$ the fall of potential between $TT' = 10 \times 10 = 100$ volts.

At a certain instant, c is positive and c' is negative, current of 10 amperes flows from c in the primary coil between cc' from c to c'.

At the same instant current of 20 amperes flows from c through the load in the secondary circuit to T' owing to the difference of pressure of 100 volts between T and TT'.

$\therefore$ In the common part TT' of the primary and the secondary circuit, there will be a current of 10 amperes flowing from T to T'; and it will unite at T' with the 10 amperes from the mains, to give the secondary current 20 amperes in the conductor cc'.

When this twenty-ampere current turns to T', it divides, one-half flowing through TT', the common part, and the other half through cc'.

If an ordinary transformer were used, there would have been in the primary coil alone as much copper as is required by the primary and secondary (*i. e.*, 20 turns) of the autotransformer Thus the copper used in the secondary coil is entirely saved, *i.e*, in this case 10 turns or 50 %, since the weights of copper in the primary and secondary windings are practically the same.

The actual saving varies with the ratio of transformation, the smaller the ratio the greater the economy.

82. Boosting and Bucking Transformers:—In *D. C.* circuits the boosting is effected by rotary machines, while in the *A. C.* circuits the same object is attained by means of the transformers. The transformer primary is connected in parallel and the secondary is connected in series with the circuit to be boosted. Voltage regulation is obtained by means of tappings taken from the primary of the transformer.

When a pressure lower than the ordinary pressure is required a "bucking" transformer is used. The lowering of the pressure is known as "bucking." The induction regulator is generally used where continuous gradation of boost and buck is required.

83 Constant Current Transformer:—Such a transformer is usually used when series arclight circuits are operated from constant potential alternating current mains. It has a counterbalanced movable secondary coil *SS*, and it delivers approximately constant current to a load circuit of invariable impedance, when the voltage between the terminals of the primary winding *PP* is constant (Fig. 2·67). The primary coil *PP* is fixed relative to the core and a secondary coil *SS* is free to move from a close contact with the primary to a considerable distance from it. When no current is taken from the secondary, it rests upon the primary When a current flows in the two coils, they repel each other and the counterpoise is so adjusted that there is an equilibrium when the current is at the proper value. If the current is greater, the coils move further away and there is an increased amount of leakage flux, and then the induced E. M F. in the secondary is lowered and the current falls to its normal value.

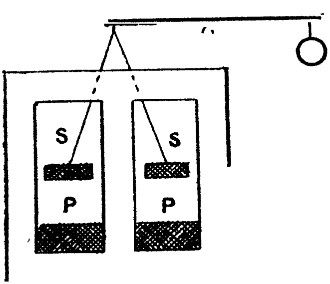
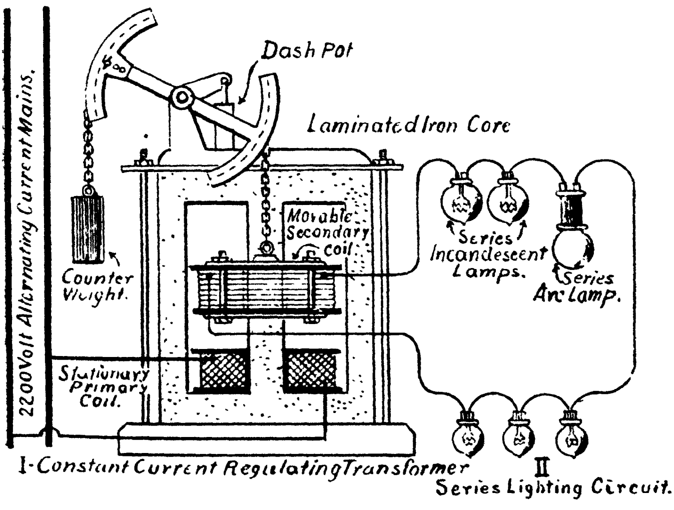


Fig. 2·67

In this the current in the secondary or the receiving circuit is automatically maintained constant when the primary is connected to a constant source of supply. The mutual inductance varies with the load.

It must have good regulation and it should be so arranged that in the event of the secondary winding becoming open-circuited, while the primary current is at normal value, the rise in voltage should not be excessive This is done by contracting the section of the core at several points, so that the iron becomes saturated at full-load primary current, and thus limits the secondary voltage to a value approximately 150 per cent. of its normal full-load value.



Constant-current Transformer

Fig. 2·68

Note:—Never open the secondary of a series transformer. If it is necessary to change connections, first short-circuit the secondary terminals.

84. Instrument Transformers:—The transformer is a source of error in the instrument readings and must be carefully calibrated The voltage drop in the transformer introduces a time-phase lag which may affect the current and voltage-phase displacement in the wattmeter. All instrument transformers should have their secondary windings grounded, because a high potential may be induced in the secondary winding, depending on the mean potential of the primary winding to ground, and the ratio between the electrostatic capacity of the secondary winding to the ground and the electrostatic capacity between the primary and secondary windings.

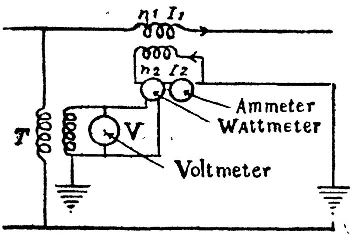


Fig 2 69

Care.—Precaution should be taken to see that the secondary winding is short-circuited before the instrument is removed, otherwise an excessive E. M. F. will be induced in the secondary winding due to the line current now becoming the magnetising current of the transformer. This is true of all series current transformers, but the E. M F. becomes particularly high in transformers designed for a high degree of accuracy and for Busher type of transformers for 1,000 amperes and above.

The ratio of a current transformer is the ratio of the primary current to secondary current.

The ratio of a potential transformer is the ratio of the primary terminal volts to secondary terminal volts. In either case, the ratio of turns is somewhat different. The ratio of current transformer generally decreases as the load or current increases. The secondary current is generally out of phase with the primary current by a fraction of a degree. This amount becomes greater as the load decreases and as the power factor of the instrument circuit increases. These variations affect principally the accuracy of the wattmeter indication.

Applications :—Instrument transformers are used for three principal purposes :—(1) to supply current and voltage to measuring apparatus ; (2) to operate regulating devices ; (3) to operate circuit protective devices. In each case there are two principal advantages to be attained by the use of transformers :—(*a*) To protect the devices in the secondary circuit against the inconvenience or danger of a direct application of the primary voltage or current. By means of voltage and current transformers the range of alternating-current ammeters, voltmeters and wattmeters can be extended, and these meters used upon circuits having larger currents and higher voltages than could be applied to the terminals of the instruments. (*b*) To enable the use of measuring, regulating and protective devices designed for one standard current and voltage for the entire range of currents and voltages used under various operating conditions, thus simplifying design and manufacture, increasing reliability and accuracy and lowering cost. Thus their use makes it possible to measure high voltage by means of instruments which can be properly insulated without difficulty and great expense

(a) **Potential Transformers** :—These are transformers of comparatively small output arranged for shunt connection to the primary lines and designed to produce a secondary voltage which accurately represents the primary voltage for application to instruments.

The general principles of the potential transformer are the same as those of the current transformer. The principal difference between the two types of transformers is in the manner of their connection to the circuit. The primary current in the current transformer is determined by the condition of the main or load circuit; the primary electromotive force is determined by the conditions of the main circuit; while the resulting primary current is determined by the electromotive force applied and the impedance of the transformer

(b) **Current-transformers** :—These are transformers of comparatively small output arranged for series connection in the primary lines, and designed to produce

a secondary current which accurately represents the primary current for application to instruments

From a purely mechanical view-point, there is little difference between the current transformer and the common power transformer ; nevertheless, electrically they have somewhat different characteristics. The current transformer consists of one or more turns on the primary and a secondary of as many turns as the desired ratio requires. The resistance and leakage reactance are very small The secondary is short-circuited through the ammeter or through a short-circuiting switch before the ammeter is removed from the circuit. In the ordinary power transformer the primary current changes with, and depends upon the secondary current. In the current-transformer, however, the effect of the secondary current upon the primary current is negligible The primary or main current is determined by the constants of the load circuit, and within practical limits is entirely independent of the current in the secondary circuit.

The function of the current transformer is to supply current to a secondary circuit of constant relative value and having constant phase relation with respect to the current in the primary. There are thus two quantities upon the constantcy of which depends the accuracy of meters connected to the secondary circuit ; namely, the ratio of the primary to the secondary current, and the phase difference between them.

The readings of ammeters and voltmeters are affected only by variations in the ratio of transformation ; the indications of power-factor meters and synchroscope are affected only by variations in the phase relation, but power and energy meters are affected by changes in both the ratio of transformation and in the phase angle.

The ratio of transformation and phase angle depend upon certain constants of the transformer, constants of the primary or load circuit, and constants of the secondary or meter circuit.

The voltage that may be applied to most types of switchboard voltmeters is from 0 to 150 volts, and the range of the current in the ammeters is from 0 to 5 amps.

85. The cause of burning out of a current-transformer if open-circuited and whether it applies to air-gap current transformer also :— In a current-transformer three different currents have to be considered, namely, the primary magnetising current, the primary load current and the secondary load current. The value of the secondary load current depends upon the impedance of the entire secondary circuit and the pressure induced in the secondary winding. The total primary current, namely, the vectorial sum of the magnetising current and the load current is fixed by the load conditions of the main circuit, but it is the small magnetising current only that is desired to be instrumental in producing a certain pressure across the secondary terminals. That is to say, the primary and secondary load amp-turns balance one another leaving only the amp-turns due to the magnetising current, to provide the requisite core magnetisation and loss. If, however, the secondary is open-circuited, the total primary current becomes active in magnetising the core, so that the pressure across the secondary terminals reaches a comparatively high value which can easily be seen from the following formula showing the relationship between the different functions involved :—

$$E = \frac{B\,A\,f\;T_s}{3{\cdot}49 \times 10^6}$$

Where, E = secondary induced pressure.
B = maximum induction density in the core in lines per sq. cm.
= ITp × constant.
A = core section in sq. inches.
f = frequency cycles per second.
T_s = number of secondary turns.
Tp = number of primary turns.
I = total primary current active in magnetising core.

Not only would a comparatively high pressure arise in the secondary windings, but the transformer

would get extremely hot on account of the considerable iron-losses arising from the high induction density in the core. The pressure waves would further contain large harmonic components *so that the peak value of the resultant wave would be much higher than indicated by voltmeter*. Precisely, the same reasoning applies to current transformers having an air gap in the magnetic circuit, but in practice the results are very considerably modified according to the width of the air-gap. On account of the air-gap magnetic flux follows a path of very high reluctance, and as most of the amp-turns are consumed in forcing the flux across the air-gap, the gap acts as an absorption device to prevent magnetic over-loading.

86 Causes of Failure of Transformers.

Troubles :—(*a*) Failures in magnetic circuit, *i.e.*, cores, yokes and adjacent damping structure.

(*b*) Failures in the electrical conducting circuit, *i.e.*, in the coils, minor insulation and terminal gear.

(*c*) In the dielectric circuit, *i.e.*, in oil and major insulation.

(*d*) Insulation failures.

(*e*) Structural failures,

Causes.—*The above defects or failures may be due to*:—

(1) Faulty manufacture, which comprises poor design, faulty material and bad workmanship.

(2) Faulty and abnormal operation which includes careless drying out and installation.

(3) Lack of adequate supervision and sustained abnormal operating conditions.

Remedies.—*Now dealing with each item separately* :—

(a) Failures of Magnetic Circuit :—

(1) In core type transformers due to break-down of insulation round the bolts inserted through the core and yokes for the purpose of clamping the laminations together.

(2) Failure of insulation between yoke and yoke due to clamping plates which produce large circulating eddy currents producing heating and damaging the coils.

(3) Loosened core-clamping bolts which set up vibration tend to weaken core insulation and produce hummings.

(4) High saturation of magnetic circuit often results in heavy magnetising current rushes, occurring when switching a transformer The phenomenon becomes more severe, the nearer the transformer is situated to the generating source

(5) Transformers for use with rotary converters are often designed with a high internal reactance for the purpose of providing means for *A. C.* pressure regulation. The high reactance is obtained by means of magnetic shunts placed in the leakage field between the primary and secondary windings; if these shunts are designed to possess a high degree of saturation, a high degree of heat will be generated, which eventually destroys the coil insulation, and causes the oil to sludge.

(6) High saturation in magnetic coil produces high harmonics of pressure or current which have very serious effects. Generally, the *third harmonic* is of importance and under abnormal conditions harmonics above third may create trouble. Third harmonics likely to give trouble are confined to 3-phase, shell type transformers and to 3-phase banks of single-phase core and shell types. Their sphere of potency may still be confined to star/star, interconnected star or interconnected star/star. In the last two, the star side only need to be considered. If the secondary neutral only of a star/star transformer is earthed, especially high pressure, the third harmonic component of magnetic flux becomes amplified, the transformer core becomes thoroughly saturated increasing the iron losses more than originally designed for raising temperature of transformer to dangerous degree, and causing deterioration of the coils.

(7) If the pressure applied to transformer must be increased appreciably with exigencies of load, the frequency must also be increased in order to avoid high magnetic saturation of core.

(b) Failures in Electric Circuit :—

(1) A short between adjacent turns of coil usually of high pressure winding may be caused by the presence of sharp edges on copper conductors. If transformer vibrates when on load or if windings are subjected to repeated electromagnetic shocks, through short circuit or switching in, these sharp edges will cut through the insulation and allow adjacent turns to make metallic contact.

(2) Short between turns may result from the dislodging of one or more turns of a coil, caused by a heavy external short circuit across the windings.

(3) Short circuit between turns due to moisture penetrating the fabric insulation of coils.

(4) In high pressure transformers, conductor insulation may deteriorate on account of corona due to sharp or slightly-rounded edges. This phenomenon becomes more accute should there be occluded air in the coils and short between turns may eventually take place.

(5) If a transformer is subjected to more or less fluctuating loads, the expansion and contraction of the copper conductors alternately compresses and releases the pressure on insulation between turns. Thus the winding becomes more and more susceptible to failure should they be subjected to electrical or magnetic shocks.

(6) Dielectric losses in the insulation may lead to excessive heating and ultimate failure of the latter.

(7) Coil conductors may be displaced violently on the occurrence of an external short circuit as the result of internal unbalanced electromagnetic conditions

(8) Short circuit between turns, break-down of winding to earth and puncture of insulators may take place due to the following *transient phenomenon.*

(*a*) Concentration of pressure on terminals end coils when switching on or when lightning discharges reach the transformer. Owing to change of surge impedance at the transition point between transformer and line, the phenomenon of reflected and transmitted pressure and current wave occurs which may produce high pressure rises in the windings, while the end coils bear the shock,

the remainder of the windings is not immune against break-down as high pressure may penetrate any part of the windings.

(*b*) The phenomenon of reflected and transmitted pressure and current waves may also occur at open-ended tapping at any point of change of surge impedance in the windings and at neutral or midpoint. Care should be taken to insulate the conductors at these points very thoroughly. The disturbing cause may be either ordinary switching in, lightning discharges, an arcing ground or chattering switch contacts.

(*c*) When switching out of circuit a highly inductive winding such as a primary, with the secondary open-circuited, the magnetising current, and consequently the magnetic flux, tends to collapse instantaneously.

(*d*) Sustained heavy overloads produce high temperature throughout the transformer. The coil insulation becomes brittle and in time flakes off the conductors in places, so producing short circuit between turns. Transformers with a high ratio of copper loss to iron loss are less able to withstand overload and, therefore, more liable to fail from this phase of operation.

(c) Failures in the Dielectric Circuit :—

Moistures entering the oil as a result of the so-called breathing action greatly reduces its dielectric strength, so that break-down from coils or terminal leads to tank or core structure may take place.

Deterioration of the oil may occur as the result of prolonged overloading of the transformer and the action is materially assisted by the presence of bare copper and lead. Excessive oil temperature produces the formation of sludge, water and acids.

Short between phases may occur if there is insufficient space or clearance between phases.

The presence of foreign conducting particles held in suspension in the oil may cause a temporary break-down due to lining, especially of these particles, between bare parts having a difference of pressure between them. Examples of this are, the flashing over under oil of terminals leads to each other and to the tank or core structure.

(d) **Insulation Failure**:—

(1) Insufficient insulation at the point of failure.

(2) Imperfect mechanical supporting and bracing and coils. Such coils, when subjected to short circuits, deflect and buckle the insulation.

(3) Poor cooling design, such that the windings have portions that are blanketed or far removed from the cooling medium, in other words, have hot spots. Thus there will be weakening of the mechanical strength of the fibrous materials of the insulation, such that at the least jar the insulation is broken and internal short circuits occur.

(4) Imperfect operation of apparatus on the line, *e.g.*, circuit breakers, etc.

(5) Undue operating conditions such as over loading, multiple operation without a proper division of the load.

(6) Want of proper care of oil, dirt, moisture, etc.

(7) Direct lightning discharge on the line.

(8) Disturbances due to operation of circuit breakers, charging of electrolytic arresters, break-down of insulators. Short circuits of the line under normal conditions cannot seriously affect the transformers; but for abnormal conditions it is very desirable to see that all protecting devices are in perfect working order.

(9) Transformers should not be operated for any great length of time on a system one line of which has become grounded. The factor of safety in such operation is only one-half of the under normal operating conditions.

(10) When the high voltage polyphase circuits supply energy for lighting, there may be trouble due to the relative electrostatic capacity of the high-tension and

low-tension circuits to each other and to earth. Thus there may be high insulation stresses in the low-tension circuits and may give shock to any-one touching the low-tension circuit to cause death.

Remedy :—Ground the secondary circuit preferably at the neutral point.

A transformer when burnt out or defective should be replaced by a spare one, if available. Examine the windings and take measurements of its open circuit losses. If there is short circuit, the loss will be abnormally high.

Locate the trouble ; the coil will be blackened due to smoke; feel the coils. after removing the exciting voltage for the point of highest temperature. If these methods fail, measure the resistance of the primary and secondary windings ; a short circuit will be indicated by a lower resistance than the normal.

Note, that in many cases, a short circuit which the transformer mày involve, may affect only a few turns in a large total number, so that the continuous current resistance may not be sensitive enough to detect it.

87. Location of Transformers :—

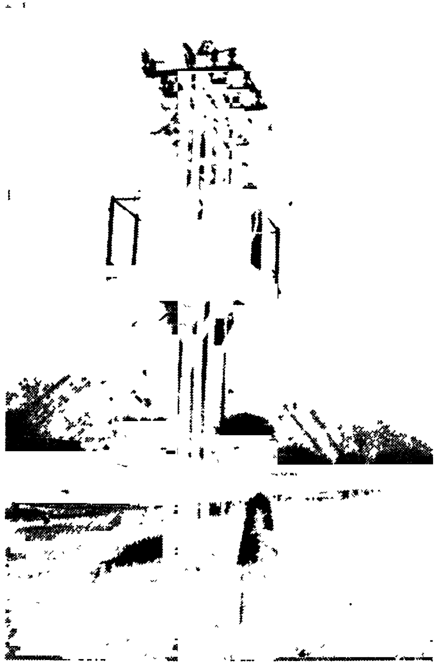
(*a*) *Step-up Transformers* :—These transformers are usually connected directly to the generators. Each generator and its transformer make one operating unit.

(*b*) *Indoor and outdoor Transformers* :—

(1) *Indoor transformers* are generally placed on the ground floor at the switch house at power stations and sub-stations.

(2) *Outdoor Transformers* :—These are used particularly with overhead transmission lines. The transformers at Bahadarabad Ganges Canal Hydro-electric Station are outside the power house.

Location of Transformers :—(1) They may be placed separately in small transformer pits under the streets and in consumers' houses.



Transformer station on Pole at Mettur

Fig. 2·70

(2) They may be grouped together in sub-stations.

(3) They may be placed on the street in the same manner as the joint and feeder pillar boxes.

(4) They may be placed on trees, as there is one at Cawnpore, supplying the military line, or may be placed on posts as at Mettur, Fig. 2·70. When two or more 75 K. V. A. or larger units are placed on poles, they are supported on two poles, on which a platform is made by wooden timber and the plant is mounted.

The choice depends upon local conditions. In large towns where the consumers are contained in small area, the sub-station arrangement will be most suitable, as large transformers may then be used and thus high efficiency, small no-load losses and good regulation may be secured.

In places or districts where the consumers are scattered, it is best to use small transformers and place

them as close as possible to the point of consumption, the transformers being of course supplied with high-tension current. Thus there will be considerable saving in the mains and the cost of the substation and attendance is eliminated. On the other hand, the cost of the transformers is considerable and there are no-load transformer losses owing to the fact that the transformers are always in circuit.

Care :—Arrangements should be made to cut out the transformers automatically in case of an internal fault or of the oil temperature becoming excessive to avoid risk of fire. Provision should be made for any oil which may escape from the tank to drain into a pit filled with broken granite. Care should be taken that no transformer fire should be able either to involve or to cut off access to the swithgear or main cable. Sometimes arrangements are made to extinguish fire in transformer chamber by injecting carbon dioxide or carbon tetra chloride. In a low-voltage network up to, say, 5 B. H. P., it is usual to serve the power and light from the same mains as far as possible. Larger power installations usually require separate transformers

The effects of an increase in altitude of the location of a transformer are to increase its temperature rise (if self-cooled) and to lower the arc-over voltage of the bushings by decreasing the air density. These effects must be considered if a transformer is operated at a higher altitude than that for which it was designed. Solid bushings have a flat voltage rating and may be used at any altitude up to 10,000 feet. The voltage rating of oil and compound filled bushings varies inversely with altitude. Care must be taken, when the ambient temperature is abnormally high, that the transformer does not overheat; either the load must be reduced or some additional artificial cooling must be provided. If the oil temperature is abnormally high, the oil will sludge unless the transformer is supplied with a conservator. The sludge will settle on the windings and cause the temperature to increase still further ; thus the effect is cumulative. If the oil in an outdoor transformer

has frozen during a period of idleness, and full load is placed on the transformer, the oil will thaw and circulate before any dangerous temperatures occur. Of course, it will be impossible for any normally-movable parts to operate : thus, no attempt must be made to change the position of ratio adjusters while the oil is frozen.

88. Installation and Maintenance of Oil-immersed and Water-cooled Power Transformers :— When the transformers have been received and unpacked, the first thing done is, they are thoroughly examined to find whether they have suffered any damage in transit. Insulators and bushings are carefully inspected and attention is particularly paid to all bolts and nuts, clamping devices and other parts which may have become loose or detached. The windings are examined to see whether they are clean, dry and free from loose bolts, nuts, nails, etc., which might have lodged there during transit or unpacking. Rust or sweat on the cover, terminal board, tank core clamps or core indicate moisture ; mildew on the press board or other insulation also indicate moisture. Indications of this nature make it imperative that the transformer be dried out, regardless of the readings of the insulation resistance obtained.

The cooling coils are inspected and tested at a pressure of 80 to 100 lbs $/\text{in.}^2$, water or oil may be used for this purpose. But oil is preferred for this purpose. When the desired pressure is reached, the supply is disconnected, and after an hour it is examined whether the pressure has fallen due to any leak in the coils or in the fittings at the end of the coils.

Before any work is commenced on the transformer, such as unscrewing nuts, etc., the transformer is completely covered, for anything dropped into the windings or core is difficult, in fact, almost impossible, to remove, and may, therefore, cause break-down. So workmen are strictly asked to empty their pockets of all loose articles before they commence work on the transformer.

Installation :—In making preparation for the installation of transformers there are a number of points to be kept in mind.

Installation, care and operation :—Tranformers are generally shipped in tanks with oil. The oil should be drawn off from the bottom of the tank and be given the general disruptive test. If the dielectric strength is not high enough, it should be de hydrated. Ifthe oil shows presence of water, it should be dried out before installation by forcing dry air at 90°*C* through the windings. The situation should be such that there are facilities for lifting the transformer out of its tank for inspection purposes and in case of break-down, for in the latter case considerable delay may occur in getting the transformer back into service, if it is not situated where it can be conveniently handled by a crane or pulley block. Where natural-cooled transformers are being installed, it is extremely important to keep ample space for adequate air circulation ; also the transformer chamber itself should be well-ventilated. It is advisable to leave a clear space of not less than two feet on all sides of natural-cooled transformers up to 1,000 K V. A. capacity, and three feet for larger size units.

89. **Erection** :—During the period between delivery and erection, the transformer should be stored in as dry a place as possible, for it is essential that the windings and oil should be thoroughly dried out before the transformer is put into service, and less time will be taken for this process if every precaution is taken to prevent the absorption of moisture during the storage period. The exact procedure in erecting any particular transformer will depend on the method which has been adopted for transportation from the manufacturer's works Where a transformer is delivered completely dried out and ready for immediate installation, providing there is no delay in putting the unit into service, the drying-out process, which is necessary in all other cases, may be omitted.

90. Troubles and Remedies :—(1) If the cooling coil is clogged—the efficiency of the coil is decreased—oil temperature is increased—flow

If a water-cooled transformer is operated at an overload, the amount of water should be increased in proportion to the load. The increased amount of water will prevent the temperature of the oil from rising as fast as the temperature of the windings, and any of the causes leading to excessive heating will have more pronounced effect under these conditions. Therefore, the transformer must be watched during over-load, to see that the oil temperature is kept well below the limit specified.

The oil temperature of water-cooled transformers requires watching to see that it is maintained at least 10° C. above the surrounding air. If necessary, the amount of water should be decreased.

There is practically no danger of condensation of moisture in a transformer, if the oil is at all times 10° C. or more above the room temperature. The oil in an idle transformer should be kept slightly warm in order to eliminate the chances of the oil becoming moist. This may be accomplished by applying voltage alone for a few hours each day.

The same general statements apply to combination of self-cooled water-cooled transformers. When such transformers are operating self-cooled, if the load exceeds the self-cooled capacity or the indicated oil temperature is 80° C. or greater, the water should be turned on immediately and the oil temperature reduced as quickly as possible to within the water-cooled limit, that is, less than 65° C.

Troubles with the Transformers :—One day in a power house it was noticed that a transformer had become very hot, although the load on the generator was only half the full-load. The set was, therefore, stopped and the transformer was first taken out and the oil removed and filtered. The insulation as well as all the connection were tested by means of megger. Defect could not be found. It was then again fitted up. The other transformer was also fitted. Insulation of the windings was tested and found all right. It was then tested to see whether the connections of any terminal had given way.

It was found out that one phase of the transformer was disabled and only two phases were working. Soldering was then properly done and the windings were again fitted up. The trouble was thus removed and the set began to work all right.

A very small transformer gave a humming sound. The screws, binding the laminæ, were tightened ; there was no more humming.

Exercises

1. Why is it advisable to use iron for the magnetic circuit of a chocking coil, and why should there be an air-gap ? Give a proof of the law that the maximum power-factor is obtained if iron and copper losses are equal. (Ord., A. C., 1909).

2. Explain the general principles of action of a transformer, and illustrate by a sketch, showing the different parts approximately to scale, stating the material of which each part is made. (Grade II., A. C., 1913).

3. Deduce an expression for the virtual value of the electromotive force in volts in a coil of n turns, due to a magnetic flux with crest value of $n \times 10^6$ lines interlinking the coil and varying as a sine function of the time at a frequency of f cycles per second. (Ord., A. C., 1911).

4. What does the term "magnetic leakage" mean, as applied to an alternating-current transformer ? Give sketches to show how it can occur (*a*) in a core-transformer with "sandwiched" windings, (*b*) in a core-transformer with concentric (cylindrical) windings. What has the leakage to do with the voltage drop ?

(Ord., A. C., 1910).

5 What is meant by the magnetising current of a transformer, and what is its phase-relation to the supply voltage ? Find the value of the magnetising current of a transformer with closed iron circuit, and of which the data are as follows :—

Primary voltage	2,200
Primary turns	320

Area of core	... ...	130 sq. ins.
Mean magnetic length of core	...	40 ins.
Permeability of iron	...	2,000
Frequency of supply...		50 periods per second.

(Ord., A. C., 1908).

6. In a single-phase transformer intended for use on constant pressure mains, explain (*a*) why the flux through the iron core is very nearly independent of the load; (*b*) why the applied potential difference on the primary and the electromotive force in the secondary are nearly 180 degrees out of phase; (*c*) why magnetic leakage produces a greater effect on the regulation with inductive than with non-inductive loads. (Ord., A. C., 1911).

7. An installation has been wired for a pressure of 200 volts, a drop of 2 per cent. being allowed from the point of supply to the farthest lamp. If a transformer is subsequently used to reduce the pressure to 50 volts, what is the percentage pressure drop assuming the same number of watts to be used in each case (Wiremen's Final, 1914).

8. A transformer of 10-kW. capacity runs 6 hours a day at full load and 5 hours a day at one-half load, while for the remaining time it runs light. What is the difference in yearly running cost between one transformer having at full load 1 per cent. iron loss and 2·5 per cent. copper loss and one having $1\frac{3}{4}$ per cent. iron loss and $1\frac{3}{4}$ per cent. copper loss, when the cost per unit (kW.-hour) is $1\frac{1}{4}$d ? (A. M. I. E. E. Exam., 1914).

9. In three-phase work one occasionally finds three single-phase transformers used instead of a single three-phase transformer. Discuss the relative advantages of these alternatives for the different cases that may arise. (Ord., A. C., 1910).

10. What is an autotransformer ? Are there any advantages in using an autotransformer for house lighting ? In what circumstances would autotransformers be inadmissible ?

11. Make a diagram of the connections of an autotransformer connected up on the same principle as an

economy coil. Is this arrangement more economical than a plain transformer with two separate windings (Wiremen's Final, 1910).

12. What is the object of using an autotransformer for a metal filament lamp installation? Make a diagram showing how it should be connected up on an installation supplied from one side of a three-wire system. (Wiremen's Grade I., 1912).

13. Describe what is meant by an autotransformer (or compensator) and indicate the currents in the windings of a 100-kW. 3-phase star-connected autotransformer having a ratio of 1,000 to 400 volts. (A. M. I. E. E. Exam., 1914).

14. Describe a simple test, requiring little power, obtaining such data that you can pre-determine the voltage-drop of a transformer at any load and any power factor. (Ord., A. C., 1909).

15. What tests requiring little power will you make to obtain the information necessary for determining the voltage drop of a transformer under any conditions of load? Give the theory of this determination (Ord., A. C., 1911).

16. The resistance of the windings of a transformer being given, explain a method by which from the short-circuit test and the open-circuit test of the transformer you can predict the voltage drop at any load and any power factor. (Grade II., A. C., 1912).

17. Explain how the efficiency of a transformer may be estimated by a full-voltage no-load test, and a test on short-circuit with full-load current in the secondary. How may the pressure regulation of the transformer on non-inductive load be found from these tests? (Grade II., A. C., 1913).

18. Explain how the voltage drop of a transformer under any conditions of load can be determined from two tests which require only little power. What is the object of dividing the primary and secondary windings of a transformer into a number of coils, and how far should this division be carried? (Grade II., A. C., 1914).

19. What do you understand by the term "regulation" of a transformer? Describe a test involving small expenditure of power by which the regulation of a large transformer can be predicted for any load and any power factor. (Final, 1st paper, 1913).

20. What points in the design of a transformer require special attention in order to get good "regulation" and high efficiency? (Final, 2nd paper, 1912).

21. A certain oil-cooled single-phase transformer rated at 75 K. V. A. 10,500/3,500 volts and 60 cycles requires the application of 700 volts on the primary winding to cause a current equal to the full-load current to flow through the secondary winding, when the latter is short-circuited, the power absorbed by the primary under those conditions being 1·8 kilowatts. Indicate by means of a vector diagram how the full-load pressure regulation of this transformer at power-factors of 70 per cent. and 100 per cent., respectively, can be approximately ascertained, and give the necessary data for such a diagram in the present case. Discuss the accuracy of the diagram you employ. (Honours, 2nd paper, 1908).

22. A 15-K. V. A. 2,200/220-volt, 50-cycle lighting transformer has a core area of 8·8 sq. in. There are 1,500 turns on the primary winding. How many secondary turns are there? Find the flux through the core. Is this an average, effective or maximum value? What is the maximum flux density? How many ampere turns per centimeter are required to set up the flux? What will be the effective value of the primary current required to produce this flux density, if the length of the magnetic circuit is 80 cm.? What percentage of full-load current is this?

23. Why does the primary current increase as the resistance of the secondary connected circuit decreases?

24. A transformer has 2 turns on the secondary for every one turn on the primary.

(*a*) The primary resistance=0·4 ohm; the primary reactance=0·9 ohm; the secondary resistance=1·4 ohms, the secondary reactance=4. The transformer on no-load takes 15 amps. and 800 watts at 220 volts. Draw the vector diagram to scale for no-load conditions.

(*b*) The load on the secondary is 45 amps. at 440 volts and 80 per cent. power factor. Draw the complete vector diagram and find the applied voltage and the primary current and power factor by scaling from the diagram.

(*c*) Give in tabulated form the order in which you drew the vectors and the reasons for their direction and magnitude.

(*d*) Why is the primary power factor almost equal to the secondary power factor on full load, but is lower at light loads ?

(*e*) Is the voltage regulation better or worse at 60 per cent. than at 80 per cent. power factor ? Draw an actual vector diagram for each case if you are not certain.

25. Why can an alternator be short-circuited safely? Is it safe to short-circuit transformer ? What are the per cent. resistance and reactance drops in the transformer of Exam. 24 ?

26. Specify the transformers required for a 200-h. p., 2200-volt, three-phase motor of 90 per cent. power factor and 92 per cent. efficiency, the line voltage being 11,000 volts.

27. If one of these delta-connected transformers is cut out so that the bank is operating open delta, to what value must the load on the motor be reduced to prevent overheating of the transformers ?

28. A 4-amp. 50-volt incandescent lamp has to be operated from a 110-volt line by (*a*) a resistance in series, (*b*) a reactance in series, (*c*) an autotransformer of 90 per cent. efficiency. Find for each case the additional loss, the current taken from the line and the power factor of the total load.

29. A 3-phase, 11,000-volt transmission line supplies 3 loads *A*, *B* and *C*. Load *A* consists of 400 h. p. of motors, 2,200-volt. 85 per cent. efficiency, 80 per cent. power factor. Load *B* supplies a transmission line at 6,600 volts to a substation where delta-delta transformers lower the voltage to 2,200 volts. The voltage is then

stepped down to 110 by delta-delta connected transformers for an *A. C.* incandescent lighting load of 500 kW. The loss in the lines is 8 per cent.

Load *C* supplies 400, 60-watt lamps at 110 volts for local lighting near the power house.

The 11,000-volt transformers are all connected *Y*-delta.

(*a*) Make a diagram of the system.

(*b*) Find currents in all line wires and all transformer windings.

(*c*) Find kilovolt-ampere ratings of all individual transformers, also the voltage ratio.

(*d*) Find the current in the 11,000-volt lines and the resultant power factor. (Note that transformer losses are neglected and primary power factor assumed equal to secondary power factor).

30. Explain how the efficiency of two similar transformers may be found by a back to back test. What arrangement may be made to vary the power factor of the circulating current (*C.* and *G. II*).

31. What is an autotransformer ? Explain clearly with vector diagrams and sketches, the distribution currents and potential difference in such a machine. (*C.* and *G. II*).

32. What kind of transformer would you use to connect a 440-volt 100 h. p. three-phase motor to 500-volt three-phase mains ? Make a diagram of the connections (*C.* and *G. II*)

33. Two 100-kW. single-phase transformers are connected in parallel both on the primary and secondary side. One transformer has an ohmic drop of 1/2 per cent. at full-load and an inductive drop of 8 per cent. at full-load current, zero power factor. The other has an ohmic drop of 3/4 per cent. and inductive drop of 4 per cent. Show how they will share the following loads :—(*a*) 180 kW. at 0·9 power factor, (*b*) 120 kW. at 0·6 power factor. (*C* and *G.*)

34. An alternate current transformer has its primary winding connected with mains whose voltage varies according to a given law, the frequency being 50. The

secondary coil as 50 turns and gives 100 volts on open circuit. The section of the transformer core is 20 sq. inches. Determine the maximum value of the induction density in the core. Prove the formula used. (London Univ., 1916).

(35) Give the theory of open and short-circuit method of testing a transformer, and show how, from the measurement taken, it is possible to calculate the efficiency and percentage drop of secondary voltage for a load of known magnitude and power factor.

A transformer to convert 10 kW. from 2,000 to 100 volts, when tested by above method, showed losses, which, for the open-circuit test at normal voltage, were 200 watts at power factor 0·7, and which, for the short-circuit test at full-load current, were 250 watts at power factor 0·25. Calculate the efficiency of the transformer for an output consisting of a full-load secondary current (lagging) at power factor 0·6. (London Univ., 1915).

(36) Two 100 kW. single-phase transformers are connected in parallel both on the primary and secondary. One transformer has an ohmic drop of $\frac{1}{2}$ °/o at full-load and an inductive drop of 8 °/o at full-load current, zero power factor. The other has an ohmic drop of $\frac{3}{4}$ °/o and an inductive drop of 4 °/o. Show how they will share the following loads: (*a*) 180 kW. at 0·9 power factor; (*b*) 120 kW. at 0·6 power factor. (C. and G.).

(37) A system supplies a load which varies in a period of 24 hours as follows :—6 a. m. to 12 noon, 1,000 kW.; 12 noon to 1 p.m. 100 kW.; 1 p m. to 6 p m., 1,000 kW.; 6 p.m. to 6 a.m 300 kW. Energy is transmitted over a line in which the losses at full load are 5,000 watts, and is transformed by a transformer having a no-load loss of 6,000 watts, and a full-load copper loss of 8,000 watts. Calculate the total losses in transmission and conversion during the 24 hours. (C. and G., 1922).

(38) A 1,000 K. V. A. and a 500 K.V.A. single-phase transformers are connected to the same busbars on the primary side. The secondary pressures at no-load are 500 and 510 volts, respectively. The impedance voltage of the first transformer is 3·4 per cent. and of the second

5 per cent. What cross-current will pass between them when the secondaries are connected together in parallel? Assuming that the ratio of resistance to reactance is the same in each, what currents will flow in the secondary windings of the transformers when supplying a total load of 1,200 K. V. A.? (C. and G., 1923).

(39) (*a*) Draw a diagram of two monophase transformers with primaries connected to 3-phase mains and secondaries connected to *two* loads taking equal currents and voltages. Explain how the arrangements equalise the three primary currents.

(*b*) Draw a diagram of a method for obtaining from 3-phase mains a supply at three times the mains frequency.

Explain the action and the advantage and disadvantage of this method.

Appendix to Chapter II

Energy of the two circuits in a transformer :—

Let the currents in the two circuits be i_1 and i_2.

The coefficients of induction are L_1, L_2, M.

There are 3 sets of electromotive forces acting :—

(1) the ohmic E. M. F. $= R_1 i_1$ and $R_2 i_2$

(2) the E. M. F. necessary to overcome the counter electromotive force of self-induction $= L_1 \frac{di_1}{dt}$ and $L_2 \frac{di_2}{dt}$

(3) the E. M. F. necessary to overcome the back electromotive force induced in one circuit $= M \frac{di_2}{dt}$ and $M \frac{di_1}{dt}$

$\therefore$ the total primary E. M. F's. $= R_1 i_1 + L_1 \frac{di_1}{dt} + M \frac{di_2}{dt}$.

The total secondary E. M. F's. $= R_2 i_2 + L_2 \frac{di_2}{dt} + M \frac{di_1}{dt}$.

The energy required to maintain the current $= Eit$; we have for the time dt

Primary energy changes $= R_1 i_1^2\, dt + L_1 i_1 \frac{di_1}{dt} dt + M i_1 \frac{di_2}{dt} dt$.

Secondary energy changes $= R_2 i_2^2 dt + L_2 i_2 \frac{di_2}{dt} dt + M i_2 \frac{di_1}{dt} dt$

The first term in each of these equations is always positive and denotes the energy dissipated as heat. The remaining terms represent the changes in the energy of the magnetic field in the time dt.

The energy given to the magnetic field in time dt is thus :—

$$dw = L_1 i_1 \frac{di_1}{dt} dt + M i_1 \frac{di_2}{dt} dt + M i_2 \frac{di_1}{dt} dt + L_2 i_2 \frac{di_2}{dt} dt.$$

The energy is between the primary and the magnetic field, and between the magnetic field and the secondary circuit, and therefore between the primary and secondary through the common magnetic field. If the primary current is I_1 and secondary current is I_2, the energy of the magnetic field is found by integrating the above equation $W = \frac{1}{2} L_1 I_1^2 + M I_1 I_2 + \frac{1}{2} L_2 I_2^2$, which represents the energy of the primary and secondary circuits considered separately ; and the term $M I_1 I_2$ is the mutual energy due to their juxtaposition so that the induction produced by one circuit threads the other circuit.

CHAPTER III

THE ALTERNATE CURRENT MOTORS

91. The chief advantages in using A.C. Motors are :—

(1) The possibility of *A. C.* transmission and distribution at higher voltages and stepping down to motor voltage.

(2) The possibility of stepping down from the voltage of motor feeders to that of lighting feeders without a lower voltage generator or its equivalent.

(3) The possibility of using induction motors which are rugged and have no commutator to wear out or introduce fire hazards.

92. Classification of the Alternate-Current Motors.—Alternate-current motors can be broadly classified under three headings :—

(1) The synchronous motors which are generally polyphase.

(2) The induction motors or asynchronous motors. These are polyphase or single-phase.

(3) The commutator motor.—This is similar to direct-current motors, and has similar characteristics, and is generally single-phase, and thus has single circuits.

93. Synchronous Motors :—Any alternating current generator, if brought up to speed, excited, and connected to a suitable alternating current supply, may be made to operate as a synchronous motor. It runs at exactly the same speed, whether loaded or unloaded, and, when heavily overloaded, it falls out of step and stops These are most commonly used as phase regulators in transmission lines or driving direct-current generators.

94. Synchronous Speed :—The speed at which a synchronous motor will run, when connected to an

alternator supplying current at a frequency f, is, where N is the speed of the motor in revolutions per minute, $N=2f\,60/p$, where p=number of poles on the motor field.

Example 1. A ten-pole motor runs from a 50-cycle alternator. Find the speed.

Solution :—

$$N=2\times50\times60/10=600 \text{ R. P. M.}$$

If the load on such a motor increases, the speed will not decrease unless the load reaches an excessive value, so that the maximum output or pull-out torque is reached, when it will drop out of step and come to rest, while the current taken will increase to short-circuit value and the torque decreases to a negligible value

95. Difference between an Alternator and a Synchronous Motor.—The latter has (1) a squirrel-cage winding in the face of the field pole intended to give good starting torque and to prevent hunting while running, and (2) a higher value of armature reaction than that of a well-designed generator of the same kilowatt rating for satisfactory operation.

This increase in armature reaction is obtained in practice by operating the machine as a motor at a lower voltage than that for which it would be operated as a generator.

96. Principle of Synchronous Motor.—If an alternating E.M.F. is impressed upon a single-phase winding, an alternate current flows through the winding and the conductors, a, b, c and d (Fig. 3·01), thus carrying currents in a magnetic field, are acted on by a force, while an equal and opposite force acts on the poles and tends to turn the rotor. The rotor is provided with field coils excited by *D.C.* and as the current in the stator is alternating, the force acting on the rotor is also alternating. Thus the rotor tends to turn first in one direction and then in the other in rapid succession and so it does not develop

a starting torque. Hence, whether loaded or unloaded, it must be started and brought up to full speed by an outside source of power. Now if the rotor moves at a synchronous speed, that is, moves through half a cycle, *i.e*, the distance between two adjacent poles, it continues to rotate; if, by the time, the direction of the current is changed in the conductor, it will have reached the adjacent pole, which is, however, at opposite polarity ; in other words, the rotor continues to move in one direction if the polarity of the poles is changed at the instant the current reverses. Thus, both the polarity of the pole and the direction of the current in the conductor are changed, so that the former condition of rotation is maintained, and, as a result, the rotor continues to rotate in the same direction. The rotor is magnetically locked with and carried round by the rotating field of the stator.

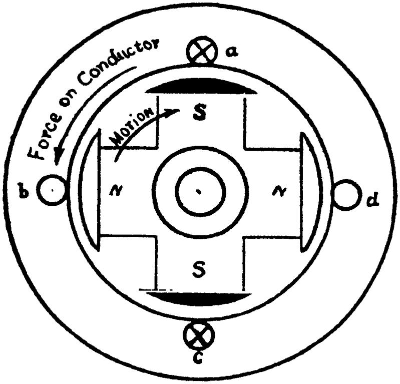


Fig. 3·01

If we join a polyphase alternator to polyphase supply mains, the machine will start and run up to full speed if it has little or no belt load.

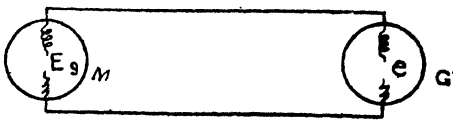
As one of the polyphase currents through the armature of the alternator dies away, it leaves a slight amount of residual magnetism in the field magnet structure if the field magnet is not excited by direct current. This residual megnetism acts upòn the growing current of the other phase or phases, and produces a torque tending to turn the armature. This action of the polyphase alternator is essentially the same as the action of the induction motor. This, however, develops only slight

starting torque. If the magnetic lock is broken, by excessive load torque, failure of *D.C.* excitation or any other cause, the motor pulls out of step and stops. Hence, specially large motors are started by an external source, the capacity of which need not be but $\frac{1}{10}$th the large motors, and they are then thrown into circuit after which the load is connected to them through a friction clutch, thus allowing it to be thrown on gradually. In smaller sizes the machine is generally self-starting without load and the load is thrown on afterwards.

The action of the motor would be unaffected by placing the *D.C.* magnet system on the stator and the *A.C.* winding on the rotor. If the stator has stationary *A C.* winding, it can be connected directly to H. T. supply, while the *D.C.* winding on the rotor can be easily supplied at a lower voltage through slip rings on the motor shaft.

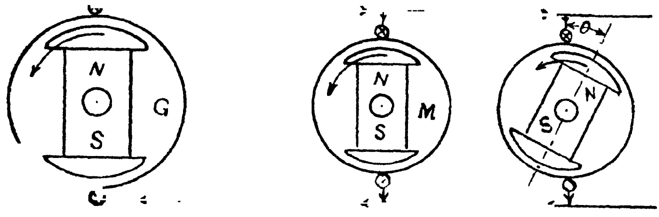
The efficiency of synchronous motors is higher than that of induction motor and their cost is lower, particularly where machines of high H. P. and low speed are concerned.

97. The Counter E.M.F. of a Motor—Suppose that the motor *M* (Fig. 3·02) is running at a synchronous speed ; as the stator winding is being cut by lines of force, an E. M. F. e is generated in the machine, which is called the counter E. M. F., as it opposes the applied E. M. F. E_g of the machine, and is of the same frequency. When the machines are equally excited $e = E_g$.



Diagrammatic Representation.

Fig. 3·02



Alternator Driving Synchronous Motor.
Fig. 3·03

When the motor has no load, supposing that there are no losses the load current taken from the line is practically zero, as it is only sufficient to overcome the friction of the machine, and e is exactly equal and opposite to E_g.

Note that when there is no resultant E. M. F. and no flow of current through the machines, the poles of the two machines will rotate together, as shown (Fig. 3·03).

Now suppose the motor is loaded, it will slow down momentarily and will swing back relatively to the generator ; e remains equal to E_g, while e is not opposite in phase as at no load, it lags its no-load value by an angle ϕ, and there is now a resultant E. M. F. E_r which sends a current through the machines, and the torque, developed due to this current, keeps the motor running at synchronous speed, but always with such a lag behind the generator as to allow a current to flow large enough to develop a driving torque equal to the retarding torque of the load. The motor thus automatically takes from the generator a current corresponding to this mechanical load.

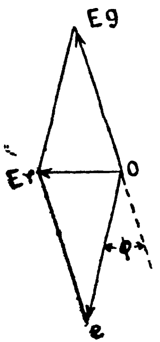
No load
Fig. 3·04

For small values of ϕ, E_r is proportional to ϕ, *i.e.*, $E_r = \phi\ E_g$ E_r sets up the current I through the armature

such that $I = \frac{E_r}{Z}$ lagging very nearly 90° behind E_r or I is nearly in phase with E_g

$$\therefore \quad P = E_g I = E_g \frac{E_r}{Z} = \frac{E_g}{Z} \times E_g \phi$$

$= E_g I_s \phi$, where I_s is the short-circuit current corresponding to normal excitation.



Full-Load Vector Diagrams for a Synchronous Motor.

Fig. 3'05

98. Period of Swing of the Rotor

Toqrue $= \frac{P}{\omega} = \frac{E_g I_s \phi}{\omega}$, where ω is the angular velocity of the rotor in radians per second.

If K is the moment of inertia of the rotating masses, this torque will be utilised in accelerating the rotor so long as there is no damping.

Hence, $K\frac{d^2 \phi}{dt^2} + \frac{E_g \, I_s \, \phi}{\omega} = 0$, this

is similar to $\frac{d^2 x}{dt^2} + n^2 x = 0$.

Hence, the frequency of the oscillation set up is $f = \frac{n}{2\pi}$, or in the case of motor $f = \frac{1}{2\pi} \times \sqrt{\frac{E_r I_s}{K\omega}}$ = frequency of the oscillation when there is no damping.

If the pole faces are provided with damping windings, there will be a retarding torque set up proportional to the angular velocity of phase swing. The effect of this torque is to damp out the oscillation, and also to diminish their frequency.

99. Vector Diagram for a Synchronous Motor :—

E_g = the E.M.F. of the alternator,

e = the counter E M.F. in the motor,

E_r = he resultant E.M.F. or vector sum of E_g and e,

I = the current which is sent through both the machines by E_r,

R_m = resistance of the motor winding,

X_m = reactance of the motor winding,

R_g = resistance of the generator winding,

X_g = reactance of the generator winding,

E_r is generally less than E_g or e owing to their phases being nearly opposite—Figs. 3'06 to 3'10.

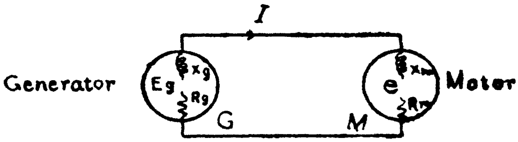
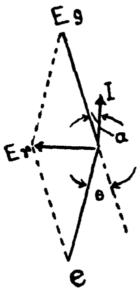
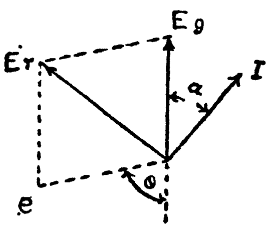


Fig. 3'06



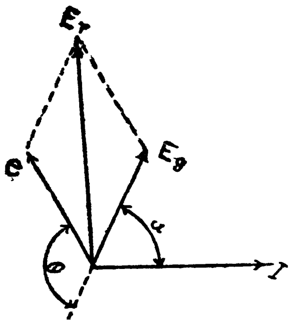
Light Load.

Fig. 3'07



Heavy Load.

Fig. 3'08



Load greater than the maximum output.

Fig. 3'09

Referring to Fig. 3'10 the angle $\alpha =$ is called the external angle of lag of the motor.

$\alpha = \angle DOC - \angle BOC = \beta - \angle BOC$, where the angle β is called the angle of lag of the armature considered as an impedance only.

If α is negative, the current leads the $P\ D$.

ϕ is called the angle of advance of E M F

$\beta' =$ internal angle of lead of the motor current at LOAD.

Draw DM and DN perpendicular to OA and OB.

$$I = \frac{E_r}{\sqrt{(R_m + R_g)^2 + (X_m + X_g)^2}}$$

The resistance is generally small compared with the reactance. Hence,

$$I = \frac{E_r}{X_m + X_g}$$

and owing to the preponderance of reactance in the armature, the current I lags behind the voltage E_r by nearly 90°, *i.e*, $\angle\beta = 90°$, nearly.

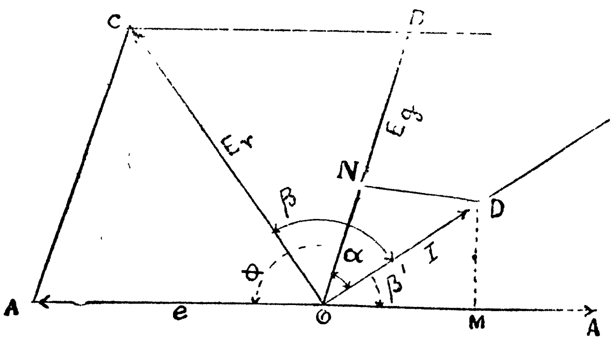


Fig 3'10

The power absorbed by the motor from the supply $= OB.\ OD \cos BOD = OB.\ ON = E_g\ I \cos \alpha$.

The power converted into mechanical power by the motor is $= OA.\ OD \cos\ (180^\circ - AOD) = eI \cos\ (180^\circ - \angle AOD) = eI \cos MOD = eI \cos (\pi - \phi - \alpha) = eI \cos \beta'$. this includes the frictional losses and the power absorbed by the iron losses, but it does not include the copper losses in the armature.

If the load on the motor is now increased, the motor swings back relative to the generator by a greater angle θ. (Figs 3·08 & 3·09) E and I are larger than before and so also is $E_g\ I \cos \alpha$, the power developed by the generator and put into the circuit for the motor.

The mechanical power of the motor includes, as in the case of direct-current motor, the friction losses and the power absorbed by the iron losses, and is less than the power taken from the supply by the amount of copper losses in the armature. Further, in calculating the commercial efficiency, the power used in supplying the excitation must be added.

100. To find the value of Er, the External and Internal angles of lag, the Input and the Output.—Synchronous motor equations :—

Let P = output of motor in watts,

L=self-induction of armature,

f=frequency of armature current,

Z=armature impedance

$$=\sqrt{R_m^2 + (2\pi f L)^2}$$

α=phase difference between I and E_g, *i.e.*, between current and the impressed E.M.F. at the motor terminals,

X_m=reactance of armature$=2\pi f L$.

$\alpha+\phi$=phase difference between I and e.

β=phase difference between E_r or ZI and I.

Then input$=P+I^2 R_m$

$$=I\ E_g \cos \alpha \qquad \ldots \quad (1)$$

$$\therefore\ I=\left\{ E_g \cos a \pm\sqrt{E_g^2 \cos^2 a - 4PR_m} \right\}/2R_m. \quad \ldots \quad (2)$$

I is always real.

$\therefore$ $E_g^2 \cos^2 a$ must be greater than or equal to $4PR_m$.

$\therefore$ $P=E_g^2 \cos^2 a/4R_m$, which is maximum when $\cos a=1$. That is, the maximun output is given by--

$P = E_g^2/4R_m$, which occurs when $a=0$, *i.e.*, when the current is in phase with the impressed voltage ... (3).

The current corresponding to maximum output is by equations (2) and (3).

$$I=E_g/2R_m.$$
$$e=Z\ E_g/2R_m.$$

101. To find the value of e corresponding to the maximum output :—The E M.F. E_r which sends the current through the motor is the resultant of the three E M.Fs. : (*a*) the impressed E.M.F., E_g ; (*b*) the counter E M.F. of the motor ; and (*c*) the drop in the motor $X_m I$, because R_m is very small in comparison with L. (Fig. 3·10).

Now E_g is in phase with I, that is $a=0$ and $X_m\ I$ is at right angles to I and e differs from I in. phase by an angle $(\phi+a)$.

The components of e along and at right angles to I are $e\ \cos\ (\phi+a)$ and $e\ \sin\ (\phi+a)$,

$$\therefore\ E_g - e\cos(\phi+a)=R_m\ I$$
$$e\sin(\phi+a)=X_m\ I$$

But when the output is a maximum,

$$E_g = 2\ R_m I.$$
$$\therefore\ e\cos(\phi+a)=R_m\ I$$
$$\therefore\ e=I\sqrt{R_m^2+X_m^2}$$

It follows that e is $>,=,<$ E_g according as Z is $>$, $=$ or $<$ $2R_m$.

$\therefore$ E_g need not be greater than the counter E. M. F. developed by the motor.

102. Value of e when the Motor is running on light load.—When the motor is running on light load, we have $P=0$, for we may neglect the friction on the bearings, etc.

$\therefore\ I^2 R_m = IE_g \cos \alpha$, and $I\ e \cos (\phi+\alpha)=0$.

But $E_g \cos \alpha - e \cos (\phi+\alpha)=R_m I$

$\therefore\ I\ E_g \cos \alpha - I\ e \cos (\phi+\alpha)=I^2 R_m$

This shows that $(\phi+\alpha)=\pm\pi/2$.

Also the maximum current at light load is $I = E_g/R_m$ (putting $\alpha=0$.), which is double the current corresponding to the maximum output.

The corresponding value of the counter E. M. F. is determined as follows :—

$$e \sin (\phi+\alpha)=X_m I.$$
$$\text{and } (\phi+\alpha)=\pm\pi/2$$
$$\therefore\ e = \pm X_m\ I$$
$$= X_m E_g/R_m$$

The minimum current at a given power is derived from $P+I^2 R_m=I\ E_g \cos \alpha$.

If P is constant, the current is minimum when $\alpha=0°$; that is, when the current is in phase with the applied E_g.

103. To find the excitation which gives the minimum current for a given load.—Here the copper loss is minimum and the efficiency is nearly maximum, as the small excitation loss is the only other variable quantity.

The output $=E_g I \cos \alpha - I^2 R$, which is a maximum when $\cos \alpha = 1$, and this gives nearly the minimum current.

$\therefore$ the output $= E_g\ I - I^2 R$

The resultant voltage $=IZ$ and leads the current by $\tan^{-1} X_m/R_m$. From the vector diagram the E.M F. of the motor $=OA=BC$.

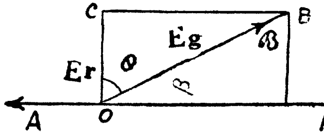


Fig. 3·11

$$=\sqrt{\left\{OC^2+OB^2-2\ OC.OB\ \cos\theta\right\}}$$

$\sin\beta=OC\sin\theta/BC$

Angle of advance $=180^\circ-\beta$.

It is always safe to work the motor at an excitation slightly above that which gives the minimum current, as in this case some more load may be put which the motor may carry without falling out of step.

Example 2. A synchronous motor supplied at 220 volts has an armature of 5 ohms impedance and ·4 ohms resistance. Find the minimum current for an output of 20 kW. and the corresponding values of the motor E.M.F. and the angle of advance.

Solution :—

$$20{,}000=220\ I-{\cdot}4\ I^2$$

or, $I^2-550\ I+50{,}000=0$

$$\therefore\ I=\frac{550\pm\sqrt{550^3-4\times 50{,}000}}{2}=\frac{550-320}{2}$$

$$=230/2=115\text{ amps.}$$

$$E_r=115\times 5=575\text{ volts.}$$

$$\cos\theta=R_a/Z_a={\cdot}4/5={\cdot}08$$

$$E=\sqrt{\left\{575^2+220^2-2\times 220\times 575\times 2/25\right\}}$$

$$=590{\cdot}5\text{ volts.}$$

$$\therefore\ \sin\beta=575\sin\theta/590{\cdot}5$$

$$=575/590{\cdot}5\sqrt{1-{\cdot}08^2}=575/590{\cdot}5\times{\cdot}99$$

$$={\cdot}97\times{\cdot}99=96=74^\circ$$

$$\therefore\ \text{angle of advance}=180^\circ-74^\circ$$

$$=106^\circ.$$

Example 3. A synchronous motor is capable of giving 25 kW. without falling out of step when running on a 220-volt 50-frequency circuit and its counter E.M.F. is then 1,200 volts. What is the resistance and self-induction of its armature and what is the curren‘ corresponding to its maximum output ?

Solution :—

$$P = \frac{E_g^2}{4\ R_m}$$

$$25{,}000 = 220 \times 220/(4 \times R_m)$$

$$\therefore R_a = 484 \text{ ohm.}$$

Again, $e = Z\ E_g\ /2\ R_m$

$$1{,}200 = Z \times 220\ (2 \times \cdot 484)$$

$$\therefore Z = 5\cdot 28 \text{ ohms.}$$

$$\therefore Z = \sqrt{(\cdot 484^2 + (2\ \pi \times 50\ L)^2}$$

$$\therefore L = \cdot 0168 \text{ henry}$$

$$e = IZ$$

$$I = \frac{E_g}{2R_m}$$

$$\therefore 1{,}200 = 5\cdot 28 \times I$$

$$\therefore \quad I = 229 \text{ amperes.}$$

104. The Circle Diagram.—In the solution of circuits it has been shown that in an alternating current circuit containing a constant applied voltage, a constant reactance, and a variable resistance, the current locus is a semicircle. This is exactly what occurs in a synchronous motor if we assume the synchronous reactance to be constant.

To draw the circle diagram, draw a straight line OF (Fig. 3·12) at an angle $\theta = \tan^{-1} X_m/R_m$ from E_g, represented to scale by OE, OE and OF are proportional to the applied electromotive force, the distance $OD = E_g/Z = I_a$, where E_g is the generator terminal or busbar voltage assumed constant (represented by OE in the figure), Z is the synchronous impedance of the motor, and I_a is the current in the motor armature The locus of the motor current I_a is a circle with centre F, and a radius equal to the motor voltage divided by the synchronous impedance or a radius proportional to the counter electromotive force at any given or required field

excitation. For different percentages of excitation, the radius of the current locus is that per cent. of FO.

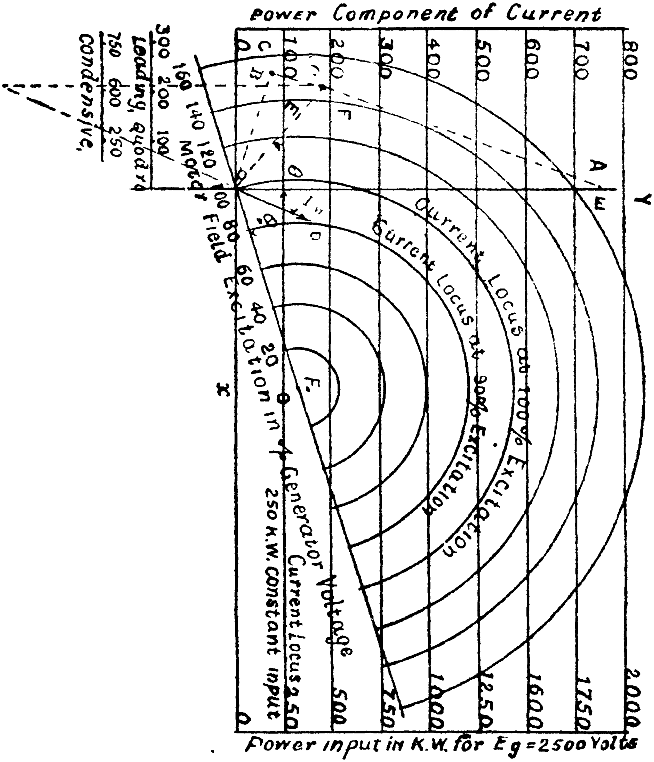


Fig. 3·12

With F as centre, a series of circles may be drawn with radii directly proportional to the motor excitation, expressed in per cent. of E_g. These circles are current loci for different motor excitations and for varying load. The component of current in phase with E_g represents power, and hence the power component and the

corresponding power input are measured directly by the projection of the current along the Y-axis. Likewise the quadrature component of the current and the corresponding reactive power are measured by the projection of the current along the X-axis. Thus the diagram shows directly the power input for any motor excitation, and also the corresponding power passing to and fro, between the motor and the generator.

Now, E, the resultant voltage causing the current to flow in the motor armature, makes an angle θ with I_m. Lay off OC equal to E_r, the impedance drop. The values of the synchronous reactance X_m and resistance R_a are known and they are at right angles to each other. Thus OC represents the vectorial sum of the reactance drop OB $(=X_m I_a)$ and the resistance drop BC $(=R_a I_a)$ and the diagram is, therefore, completed. AC is the counter electromotive force of the motor.

***105. The V and O Curves.**—The armature current in a synchronous motor giving constant mechanical power is a minimum if the power factor is unity. The power factor may be varied with corresponding change in the armature current by varying the field excitation of the motor. Curves plotted with the field excitation as

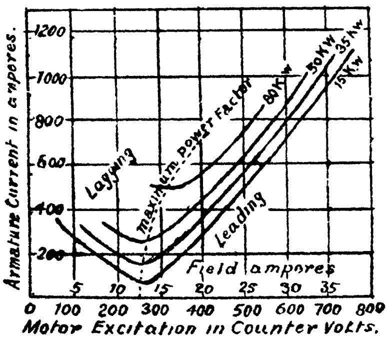
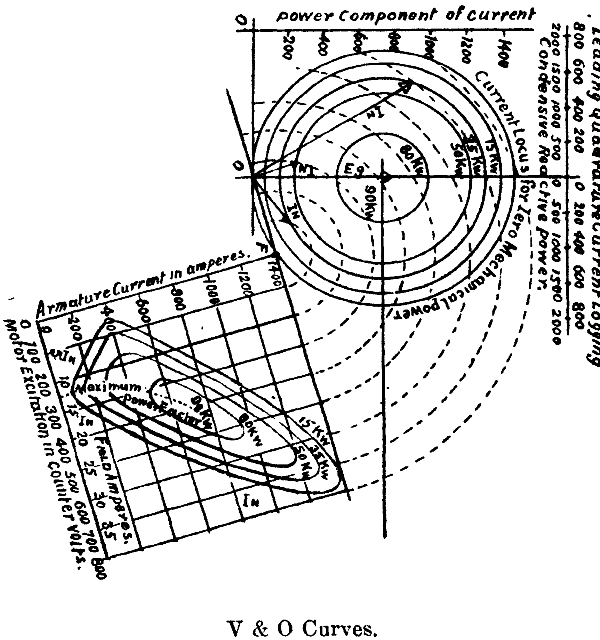


Fig. 3·13

* C. E. Magnusson's Alternating Current Motor.

abscissæ and the armature current as ordinate for a constant load, assume a form like the letter *V*, Fig. 3·13, and are known as the *V* curves of a synchronous motor. A series of curves may be obtained for a number of loads.



V & O Curves.

Fig. 3.14

The voltage or field excitation of the motor is laid off on a line from the origin to the intersection of the current locus for a constant load, with the loci for different field excitations, and this distance used as ordinate in obtaining a point on the *V* curve. By plotting the values of the current for all points on the circular load loci, the *V* curves are converted into closed curves, sometimes called the *O* curves of the synchronous motor, Fig. 3·14.

The method of construction enables the following important values to be obtained for any particular load :—

(*a*) the minimum possible excitation ;
(*b*) the maximum possible excitation ;
(*c*) the excitation for minimum current ;
(*d*) the magnitude of the currents for (*a*), (*b*) and (*c*), and the corresponding power factors.

106. Advantages of the Synchronous Motor :—

(1) It gives absolutely constant speeds at all loads up to the maximum.

(2) It is very convenient for large powers, where the machine can be started up without load, and once started, run for long periods.

(3) If the field be strongly excited, it acts as condensers in so far it takes a leading current, and thus it tends to compensate for lagging current due to induction loads on other parts of the system. The power factor of the motor and of the whole supply system may be improved by simply varying the degree of field excitation of the motor and can be made approximately unity at any load.

(4) The efficiency of the machine may be made somewhat higher than that of induction motors.

(5) The motor will exert a steady maximum torque several times larger than full-load torque before coming to a sudden standstill, due to overload ; but a sudden overload sufficient to momentarily reduce its speed, stops it.

(6) It is specially adapted to high-voltage winding. High-voltage supply at 2,200, 3,300, 6,600 or even 15,000 V. can be used without stepdown transformer in motors of 200 H.P. or more.

107. Disadvantages of Synchronous Motor.—

(1) It is usually not self-starting, unless wound for two or three-phase current and is fitted with a damper winding, even then it cannot start under a heavy load.

(2) It requires more or less skilled attendance and more auxiliary apparatus.

(3) It cannot be started under heavy load, as it has a small starting torque. Arrangements must be made for switching on the load after the motor is synchronised. Thus it is unsuitable for most workshop practice

In cases where the motor should be frequently stopped, they are unsuitable.

(4) The motor must run at a constant speed, if so, it is subjected to sudden heavy overloads, the result would be constant sudden stopping of the machine, with resultant troublesome starting up again.

(5) The motor will stop altogether if overloaded sufficiently to prevent the motor, keeping pace with the stator field.

(6) Continuous current is necessary for field excitation.

(7) It is subject to a trouble known as "hunting."

(8) It is not a variable speed motor, a fact which renders its operation very unsuitable for many kinds of work.

(9) A momentary opening of the circuit would probably cause the motor to stop immediately.

108. Special applications for which the Synchronous Motor is suitable.—

(1) It is conveniently used in transformation of high-tension *A.C.* supply to low-tension *D.C.* supply in power substations.

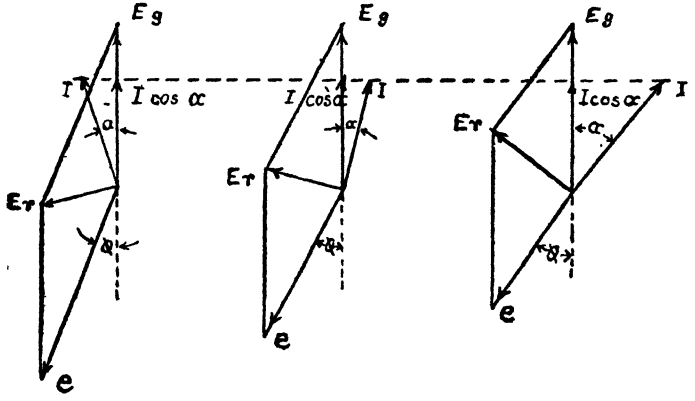
(2) For driving large pumps, fans, compressors, etc., which require a constant speed and form a steady load.

(3) For improving the power factor of the system. But there is no advantage in leading power factor unless in the case of private generation there are lagging loads to be compensated. In the case of purchased supply the supply authority allows a rebate for high or leading power factor. A leading power factor is just as objectionable as a lagging power factor. But under most practical condition a leading power factor is valuable in helping by its compensating effect to approach the ideal of unity.

(4) The motor is adaptable for direct-coupled low-speed driving, the power factor of low-speed induction motors being low ; high-speed synchronous motors are, however, available if required for such purposes as driving centrifugal pumps. Synchronous motors can be built economically for speeds down to 100 R.P.M., or so.

109. Comparison of Synchronous and D. C. Motor.—If the field of a direct-current motor be weakened, the motor will speed up in order to keep the E. M. F. at a proper value. But if the field strength of a synchronous motor be changed, the speed cannot vary as the motor must run in synchronism with the alternator that supplies it with current. The change of phase difference between the armature current and the applied E. M. F. always enables a synchronous motor to automatically adjust itself to changes of load and field strength.

110. Operation of Synchronous Motor under different excitation.—(1) Let the excitation of the motor be normal, so that $e = E_g$, that is, of such a value that the current in the motor armature is exactly opposed



Over-excited Unity Power Factor Under-excited

Effect of Excitation on the Power factor of a Synchronous Motor.

Fig. 3'15 Fig. 3'16 Fig. 3'17

in phase to the counter electromotive force e of the motor (unity power factor), then the effective value of this current will be a minimum and hence the efficiency of the motor, generator, and transmission lines will be a maximum as I^2R loss will be a minimum. Thus, this is the most efficient condition of operation.

There is one value of exciting current for which the armature current is a minimum. In motors of good regulation, this value of exciting current varies very slightly with increasing load.

(2) Let the motor be over-excited. As the motor is running in synchronism with the generator, its speed cannot change. The result is that the voltage e must now be greater than E_g. The load on the motor is unchanged so that $E_g I \cos_a$ is constant. The current I leads the generator voltage E_g. Thus the over-excited synchronous motor draws a leading current from the line and thus it acts to a certain extent like a condenser.

The power factor of the motor is a dependent one, that is, on its field excitation and as such it is changed by changing its field excitation and by properly adjusting the field excitation ; the counter-electromotive force of the motor can be made considerably greater than the impressed electromotive force. Thus by over-excitation it (*a*) improves the power factor, (*b*) increases the generator capacity, (*c*) diminishes the current in the line. (*d*) If the motor is under-excited, there is a lagging current as in an inductance coil.

111. Overload Capacity.—The maximum overload capacity of the machine increases with the value of *D.C* field current, until magnetic saturation is reached ; up to this point, the locking action between the rotating *A.C.* field and the rotor increases with the *D.C* field current. Under favourable circumstances a synchronous motor can carry a momentary load of $1\frac{3}{4}$ to $2\frac{1}{4}$ times its rated H. P without pulling out of step.

When running synchronously, the maximum or pull-out torque of a synchronous motor varies with the

D.C. field and the *A C.* supply voltage, instead of with the square of the latter as in the case of induction motors. This is a distinct advantage where the supply voltage is apt to be low. For example, $12\frac{1}{2}$ °/o decrease in voltage reduces the maximum torque of a synchronous motor to $87\frac{1}{2}$ °/o of its full voltage value, whereas that of an induction motor would be reduced to $76\frac{1}{2}$ °/o.

112. Reversal of Synchronous Motor.—A synchronous motor can be reversed by interchanging two of the stator supply leads (in the case of 3-phase machine). If this be done while the motor is running, the machine is plugged, *i.e.*, stopped by reversal of torque; this is a method which imposes heavy mechanical stresses on the motor and on the driven loads.

113. Rotary Condenser or Synchronous Compensator:—A synchronous motor that operates to correct power factor only and does not pull any mechanical load is called a synchronous condenser. The synchronous motor is often used for compensating the lagging current of an inductive circuit by supplying the wattless magnetising current, and thus relieving the transmission cables as well as the generator of "idle current."

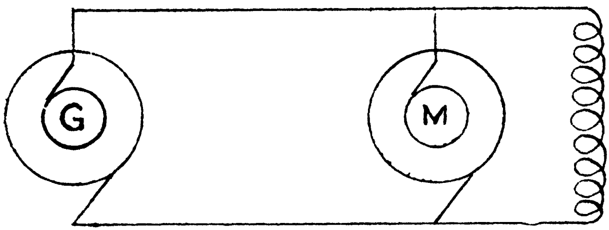
Use:—

(1) To compensate the effect of induction motors and lightly-loaded transformers in long transmission lines.

(2) To improve the regulation of voltage at the receiving end of a transmission line.

When it is to be used for improving the power factor, it is installed at the transformer point. They should be installed on the distributing system network as near as possible to the centre of gravity of the load to benefit the entire, generating, and transmitting apparatus as the power factor is improved only of that portion of the transmission system, which is between the alternators and the synchronous motor, and it is connected on the secondary side for (1) it will reduce the output required from the transformer, (2) it will be more

economical, as the insulation for a low-pressure winding is less costly.



Connection Diagram.

Fig. 3'18

It is most effectively used as a condenser when it is not required to deliver any mechanical power as a motor. When it is used to deliver mechanical power and also to take a leading current for compensating the effect of lagging current, the load is limited to 70'7 per cent. of the full-load rating of the motor. For, as the motor takes its full-load rated current and 70 7 per cent. of its full-load rated power and its field magnet is over-excited, then the current is 45 degrees ahead of the E. M. F., the power factor of the motor is 70'7 per cent., the power component of the current is 70'7 per cent. of the full-load current, and the wattless component of the current which is 90 degrees ahead of the supply E. M. F. is also 70'7 per cent. of the full-load current.

When idle current synchronous machines are used for voltage regulating purposes, they are required to run part of the time with leading current and part of the time with lagging current They are then called synchronous phase modifiers. Synchronous phase modifier differs from synchronous machines as they are built for the highest economical speeds and equipped with smaller shafts and bearings. Special attention is given to high overall efficiency. These are designed to give their full-load output at leading power factor and can then carry

about 50 % of their rated capacity lagging. It maintains a constant terminal pressure. At times of light load the machine would be operated under-excited, drawing a lagging current to pull down the voltage, while under load they will be over-excited and draw a leading current, to raise the terminal pressure This constant voltage regulation is usually made automatic by installing voltage regulators such as Tirril regulators operating on the field current of synchronous phase modifiers, and having their control magnets actuated by the phase voltage of the circuit, in which the pressure is to be maintained constant.

114. The Methods of Starting Synchronous Motor :—

(1) By using the exciter as a motor during starting. This is suitable when a *D.C.* supply is available.

(2) By using a small induction motor. It is directly coupled to the synchronous motor and has one pair of poles less to run at the synchronous speed.

(3) By opening the field circuit and connecting the armature to a supply at, say, one-third of the normal voltage.

115. Self-starting Synchronous Motors :— Very often a squirrel-cage winding is used in the field pole faces, to give powerful starting torque by the induced currents therein. Such winding has fairly high resistance to start well from rest, but low resistance to give powerful synchronising, that is, to pull the load promptly into synchronism. If alternating E. M. Fs. are applied to the stator when the field coils are not excited, the machine will start up as an induction motor and will attain practically synchronous speed

The most important advantage of self-synchronising motor is that they can start against more than full-load torque, while an ordinary synchronous motor with dampers cannot overcome more than half the full-load torque when coming into synchronism. These are, however, all more suitable for polyphase than for monophase circuits.

The single-phase motor cannot be made self-starting in this way.

116. Crompton Self-Starting Synchronous Motors.—The "Crompton" patent self-starting synchronous motor is of exactly similar mechanical construction to an ordinary three-phase induction motor, but has mounted on the same bed-plate, an exciter driven by the synchronous motor.

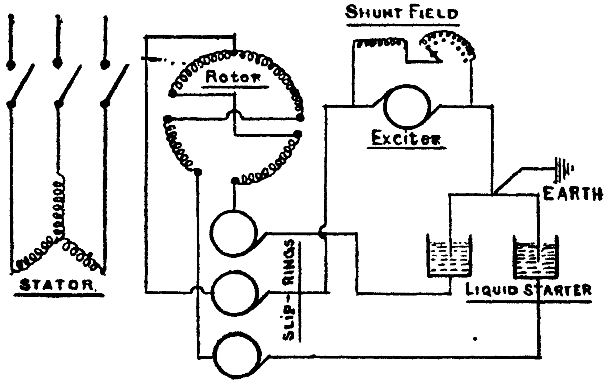


Diagram of Connections.

Fig. 3·19

The stator, both as regards winding and constructions, is the same as for an induction motor; but the rotor is wound two-phase, three-wire, the neutral point being connected direct to one terminal of the exciter and the two free ends being connected to the two ends of a two-phase liquid starting resistance, the neutral point of the latter being connected to the other terminal of the exciter.

It will be noticed that the advantage of having the rotor wound two-phase is that all conductors have an equal current flowing through them; and the neutral of the liquid starter, being necessarily earthed, the exciter is also at earth potential, which is rather an important point, as the slip-ring voltage at starting is somewhat high.

The machine starts up as an ordinary three-phase induction motor, exerting a starting torque up to $2\frac{1}{2}$ times full-load torque, and on reaching a speed nearly equal to full speed, the direct exciter current causes the rotor to take definite poles and the machine pulls into synchronism.

There is no difficulty in designing these machines to pull into synchronism against full-load torque

The advantages of having the power factor under control and of being able to draw a leading current are self-evident.

There is also the advantage that the radial air gap may be made to $2\frac{1}{2}$ times longer than is permissible with an induction motor of equal output capacity.

One of the advantages is that by the arrangement of two-phase rotor windings, no high potential exists at any time on the exciter, or field regulator. This is rather an important advantage over other types.

With rĕgard to the relative effect of a synchronous motor running light and running heavy, each case must be considered individually, but speaking generally, it may be taken that a synchronous motor will raise the power factor of the system approximately the same whether running light or running fully-loaded.

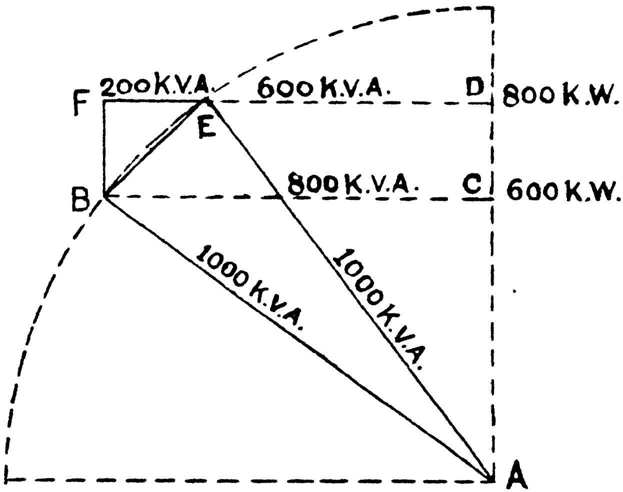
The starting current goes down relatively as the torque increases above full-load torque owing to the power factor becoming higher. Compared with induction motors, if an ordinary three-phase induction motor takes $1\frac{1}{2}$ times full-load current to start against full-load torque, a synchronous motor would take $1\frac{1}{2}$ to twice full-load current. This ratio between induction motor current and synchronous motor current at starting becomes nearer unity, as the starting torque increases, and is about the same in the two machines against twice full-load torque.

Example 4. Determine the size of motor required to raise the power factor from 0·6 to 0·8 of a 1,000 K V.A. set and thus to add 200 kW. of additional motor plant, without increasing the generating plant, which is already

carrying full-load current at 600 kW. load. The graphical method is usually adopted.

Solution :—

In Fig. 3·20, the line AB represents the initial conditions of load of the generator, *viz.*, 1,000 K.V.A. which is drawn at an angle to AC which represents the true power, such that $AC/AB = 0{\cdot}6$



Vector Diagram.
Fig. 3·20

AB=1,000 K.V.A. represents total K.V.A.
AC=600 kW. represents true or kW. load.
CD=800 K.V.A. represents wattless K.V.A.

As the final conditions require a true load of K.V.A. at 0·8 power factor = 800 kW., AC is produced to D making AD = 800 kW., AE is drawn at an angle to AD such that $AD/AE = 0{\cdot}8$.

AE = 1,000 K.V.A. represents total K.V.A.
AD = 800 kW. represents true or kW. load.
DE = 600 K.V.A. represents wattless K.V.A.

To ascertain the size of synchronous motor join BE. At B draw a line BF parallel to CD and cutting DE produced at F.

Then $BF = CD = 200$ kW. input

$FE = BC - ED = 800$ K. V. A.—600 K. V. A.

$= 200$ K. V. A.

$BE = \sqrt{200^2 + 200^2} = 283$ K. V. A. total.

The angle FBE represents the angle of lead of the synchronous motor, which would have a power factor= 200 kW /283 K. V. A. = 70·7 % or, in other words, 70·7 leading.

Allowing 90 % efficiency, the motor would be capable of developing 240 B. H. P.

117. Comparison of Methods for Correcting Power Factor :—

I. For Individual Induction Motors.—

(1) Large slip-ring motors—(*a*) Connect a rotary or static condenser in parallel with the stator winding ; (*b*) instal a phase advancer in the rotor circuit.

(2) Small slip-ring or squirrel-cage motors—Use a static condenser. Note that for squirrel-cage motors, phase advancers cannot be used.

II. For a system as a whole.—

(1) For short transmission lines with moderate drop of pressure.—Improve the power factor of the individual or groups of induction motors.

(2) In long lines with excessive pressure drop.— The rotary condenser is the best.

*** 118. Power Factor Correction**:—

(a) Constant Kilowatts

OA=a current of I_1 amps. lagging by an angle ϕ_1 behind the voltage OE (the corresponding power factor being $\cos\phi_1$)=the original value of the total current.

OM=wattless component$=I_1 \sin\phi_1$.

*A. E. Clayton's Power Factor Correction.

If the power factor is improved, the watt component OB retains its value, but the wattless component shall be reduced by an amount AC OC represents the new value of the current lagging by an angle ϕ_2 behind the voltage.

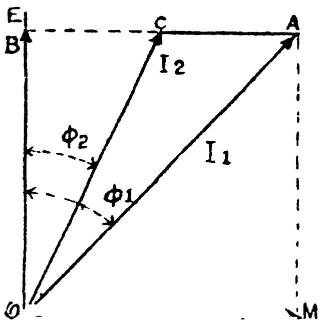


Fig. 3·21

The new value of the total current

$$=I_2=OB/\cos\phi_2$$
$$=I_1\cos\phi_1/\cos\phi_2.$$

The wattless component of the current

$$=BC=OC\sin\phi_2$$
$$=I_2\sin\phi_2$$
$$=I_1\cos\phi_1\sin\phi_2/\cos\phi_2$$
$$=I_1\cos\phi_1\tan\phi_2.$$

Let x = power factor before correction.

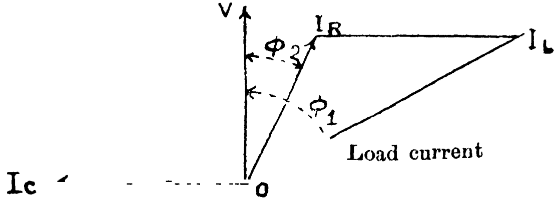
y=power factor after correction.

Reduction in wattless component

$$=I_1(\sin\phi_1-\cos\phi_1\tan\phi_2)$$
$$=I_1(\sqrt{1-x^2}-x/y\sqrt{1-y^2})$$

where, I_1 is the original value of the total current.

Example 5. A three-phase low-speed induction motor on full-load has an output of 500 H. P. and efficiency of 92 per cent. and a power factor 0·8. Calculate



Condenser Current
Vector Diagram for Condenser in Parallel with Motor.
Fig. 3·22

the capacity of the condensers necessary to correct the power factor to 0·92, the supply being 6,600 volts. 50 cycles per sec.

Solution.—

The full-load K.V.A. $=(500\times0{\cdot}746)/(0{\cdot}92\times0{\cdot}8)$ $=507$ K.V.A. The K.V.A. of the condenser

$$= \text{original K.V.A. } (\sqrt{1-x^2}-x/y\sqrt{1-y^2})$$

$$= 507\left\{\sqrt{1-0{\cdot}8^2}-(0{\cdot}8/0{\cdot}92)\sqrt{1-0{\cdot}92^2}\right\}$$

$$=507\times{\cdot}261=132 \text{ K.V.A.}$$

The capacity of the condenser load is, therefore, 132 K.V.A. total, or 44 K.V.A for each phase. If the condensers are star-connected, each group receives $6{,}600/\sqrt{3}=3{,}811$ V. and the capacity per phase.

$$= \frac{\text{K.V.A.}\times10^9}{2\pi\times50\times V^2}$$

$$= 44\times10^9/\left\{2\pi\times50\,(3{,}811)^2\right\}$$

$$= 10 \text{ M Fds.}$$

The total capacity of the condensers required, if for star-connection, is, therefore, 30 M. Fds.

If the condensers were connected in delta, the capacity required would be one-third of that for star grouping, since the capacity varies inversely as the square of the voltage. Normally, however, the cost of the condensers will not be influenced materially by the method of grouping employed, whether star or mesh; the mesh arrangement consisting of $\sqrt{3}$ times as many component condensers, each designed for $1/\sqrt{3}$ times the capacity of the component condensers used for the star connection.

(b) Costant kilovolt amperes.

Let

V_p = volts per phase.

I_1 = original value of current.

ϕ_1 = original value of current lag.

ϕ_2 = "corrected" value of current lag.

By improving the power factor the system can be increased from $V_p I_1 \cos\phi_1$ to $V_p I_1 \cos\phi_2$.

OV_p=the voltage.

OA=original current lagging by an angle ϕ_1.

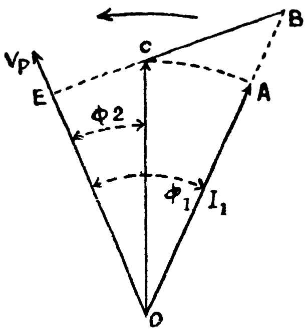


Fig. 3·23

OC=final corrected current having the same value as OA but with a lag of ϕ_2 behind the applied voltage.

OB=the current in phase with OA which has the same watt component as OC.

$=OA \cos\phi_2/\cos\phi_1$.

In order that the load on the system may be maintained at I_1 amps. when the power factor is improved from $\cos\phi_1$ to $\cos\phi_2$, it is necessary to compensate for a wattless component represented by CB.

$CB=EB-EC$

$EC=I \sin\phi_2$

$EB=OB \sin\phi_1$

$OE=I_1 \cos\phi_2=OB \cos\phi_1$

$\therefore\ OB=I_1 \cos\phi_2/\cos\phi_1$

and $EB=I_1 \sin\phi_1 \cos\phi_2/\cos\phi_1$

$\therefore$ the necessary compensation of the wattless component

$=I_1 (\sin\phi_1 \cos\phi_2/\cos\phi_1 - \sin\phi_2)$

$=I_1 (y/x\sqrt{1-x^2} - \sqrt{1-y^2})$

The wattless K.V.A. to be compensated$=P\ \{\sin(\phi_1-\phi_2)\}$ K.V A. Thus by compensating the wattless component the capacity of the plant is increased from $P \cos\phi_1$ to $P \cos\phi_2$. This new load is at the original power factor ϕ_1 or would increase the capacity to $(P \cos\phi_2/\cos\phi_1)$; in this case the increase is

$P\{(\cos\phi_2-\cos\phi_1)/\cos\phi_1\}$ K.V.A.

Example 6. The normal power factor of a system is 0·75 and the full designed load of 1,000 K.V.A. is being handled. It is desired to connect more 0·75 power factor load to the system so that 950 kW. can be handled, by installing condensers so that the power factor of the new total load shall be raised to 0·95. Calculate the necessary capacity at 6,000 volts, 50 cycles per sec.

Solution.—

The value of the wattless K.VA. to be compensated is

$$1{,}000\,(\sin\phi_1 \cos\phi_2/\cos\phi_1 - \sin\phi_2)$$

$$=1{,}000\left\{\sqrt{1-\cdot75^2}\times(\cdot95/\cdot75)-\sqrt{1-\cdot95^2}\right\}$$

$$=1{,}000\,(\cdot836-\cdot312)$$

$$=1{,}000\times\cdot524=524 \text{ K.V.A}$$

$=$the total capacity necessary at 6,000 volts

$$=524\times10^9/\left\{2\pi\times50\times(6{,}000)^2\right\}$$

$$=46\cdot5 \text{ M. Fds.}$$

If the condensers were arranged in three-phase mesh, the system being three-phase, the capacity per phase would be 15·5 M.Fds., and if the condensers were star-connected, the capacity per phase at the subsequent reduced voltage would be 46·5 M.Fds.

Example 7. An installation of 1,000 K.V.A. works on a load of 0·8 power factor. Determine the capacity of the power factor correcting apparatus to be used to improve the power factor from 0·8 to 0·95.

Solution.—

The load at 0·8 power factor$=0\cdot8\times1{,}000=800$ kW. By improving the power factor the load is $0\cdot95\times1{,}000=950$ kW. At the normal power factor of the load (*i.e.*, 0·8) this load of 950 kW.$=950/0\cdot8=1{,}187$ K.V.A.

The corresponding wattless component$=1{,}187\times0\cdot6$
$=712$ K.V.A.

At the power factor of 0·95, K.V.A. for 950kW.
$=950/0\cdot95=1{,}000$ K.V.A.

The wattless component$=1{,}000\times0\cdot313$
$=313$ K.V.A.

Hence, the wattless component must be compensated by the difference between the wattless component of 950 kW. at 0·8 power factor and of 950 kW. at 0·95 power factor, that is, by 712−313 =399 K. V. A.

(c) The Improvement of Power Factor by the use of Rotary Condenser :—

Example 8. Take the case of Example 6.

Solution.—

The original load is 1,000 K. V. A. $\cos\phi_1$

$$=1{,}000 \text{ K. V. A.} \times 0{\cdot}75 = 750 \text{ kW.}$$

It is desired to increase the load to 950 kW. The power factor of the load itself remaining at 0·75. The new value of the actual load is thus 950/0·75=1,267 K. V. A. at $\cos\phi_2 = 0{\cdot}75$.

The new load may be met by (1) increasing the capacity of the whole system including alternators, transformers and transmission line in the ratio of 1,000 to 1,267.

The load may also be handled by (2) existing plants and transmission line by installing a rotary condenser at the distributing substation, the condenser being of such capacity as to raise the power factor from 0·75 to 0·95, so that the combined load on the system now becomes 1,000 K.V.A. (where $\cos\phi_2=0{\cdot}95$).

The wattless component of 1,267 K. V. A. (where

$$\cos\phi_1 = 0{\cdot}75) = 1{,}267 \text{ K. V. A} \times \sin\phi_1$$
$$= 1{,}267 \times 66{\cdot}1/100$$
$$= 837 \text{ K. V. A.}$$

and the wattless component of 1,000 K. V. A. $\cos\phi_2$

$$=1{,}000 \times 31{\cdot}3/100 = 313 \text{ K. V. A.}$$

Hence, to compensate the wattless current corresponding to 837—313=524 K. V. A., we have

(1) to provide an extra 267 K.V.A. of generating and transforming plant (if transformers are used) and to increase the capacity of the transmission line so as to deal with a further 524 K. V. A., or

(2) to instal a 524-K. V A. rotary condenser together with the necessary exciter, starting motor, etc.

It should be noted, however, that rotary condensers cannot be made commercially for small values of the K. V. A. rating. Thus these are used for correcting the power factor of the system as a whole

Example 9. Two 200-H P. 450-volt induction motors operate at 85 per cent. power factor and 87 per cent. efficiency. Find the saving in transmission line copper when one of the induction motors is replaced by a synchronous motor, the efficiency of which is 85 per cent. when over-excited, so as to compensate for lagging current of the other induction motor. Also find the rated output of the synchronous motor and its power factor.

Solution :—

$I = 400 \times 746/0{\cdot}85 \times 0{\cdot}87 \times 450 = 896$ amps. for two induction motors.

$I = 200 \times 746/0{\cdot}87 \times 450 + 200 \times 746/0{\cdot}85 \times 450$

$= 381 + 390$

$= 771$ amperes for one induction motor and one synchronous motor.

$R'(896)^2 = R''(771)^2$ or $R' = (771/896)^2 R'' = 0{\cdot}74\ R''$, *i.e.*, the weight of copper is approximately 26 per cent. greater for two induction motors than for one induction motor and one synchronous motor. $Sin^{-1}\ 85 = 0{\cdot}52$.

The P. F. of synchronous motor is

$$= \frac{390}{\sqrt{(390)^2 + (448 \times 0{\cdot}52)^2}} = 390/459 = 0{\cdot}85.$$

Rating of synchronous motor $= 200/0{\cdot}85 = 235$ H. P.

Example 10. If 1,000 horse-power of 2,300-volt single-phase induction motors are operating at the end of a transmission line, find the current in the line and also the generator capacity required, if the average power factor is 80 per cent. and the average efficiency is 90 per cent. If 500 horse-power of the load is driven by a synchronous motor, the power factor of the system may be raised, if this motor is over-excited and made to act as a condenser.

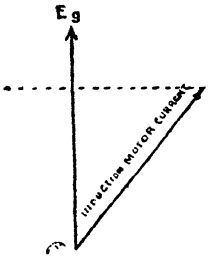


Fig. 3·24

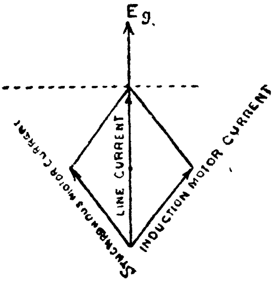


Fig. 3·25

The output of the motors is 1,000 H. P.

The input to motors is 1,000/0·9=1,111H. P. =830 kW.

The generator capacity required = 830/0·8 = 1,040 K.V.A.

The current in the line=1,040×1,000/2,300=452 amperes,

If the power factor of a synchronous motor be made 80 per cent. with the current leading the vector diagram of the load is shown in the diagram, Fig. 3·25.

The induction motor output =500 H. P.

The induction motor input=(500/0·9) × (746/1,000) =415 kW.

The current for these motors=415×1,000/2,300×0·8 =225·5 amperes.

The current for the synchronous motor is also 225 amperes, but it leads by an angle 0·8, whereas the current for the induction motor lags by the same angle.

The resultant current in the lead = 2 (225·5×0·8) = 360·8 amperes.

The generator capacity required=360·8×2,300/1,000 = 829·84 = say, 830 K. V. A.

Example 11. If the load on a 450-volt system consists of a synchronous motor taking 100 kilowatts at unity power factor and induction motor taking a total of 200 kilowatts at an average power factor of 0·7, find the power factor of the whole load, and the values to which this rises when the synchronous motor is made to take leading currents with power factors of (*a*) 0·8, (*b*) 0·6.

If the armature resistance of the synchronous motor is 0·1 ohm, and the resistance of the transmission mains, etc., 0·06 ohm, find the changes in the losses in both.

Solution :—

If the current taken by the synchronous motor $=100\times1{,}000/450=222{\cdot}2=AX$

Current taken by induction motor
$=(200\times1{,}000)/(450\times0{\cdot}7)=635$ amps. $=OC$.

Power component
$=0{\cdot}7\times635=444{\cdot}5=OA$.

Reactive component
$=\sqrt{\{635^2-444{\cdot}5^2\}}=453{\cdot}4$

$\therefore$ Total current
$=\sqrt{\{(222+444{\cdot}5)^2+(453{\cdot}4)^2\}}$
$=806$ amps. nearly.

$\therefore$ Power-factor of the whole load $=666{\cdot}7/806=0{\cdot}82$ or Power-factor $=(100+200)\times1{,}000/806\times450=0{\cdot}82$.

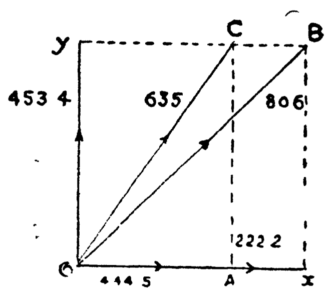


Fig. 8·26

(*a*) The total current in the synchronous motor $=222{\cdot}2/0{\cdot}8=277{\cdot}7$ amps. $=OB$ (Fig. 3·27).

Capacity component $=\sqrt{\{277{\cdot}7^2-222{\cdot}2^2\}}$
$=166{\cdot}5$ amps. $=OF$.

Hence the total current in mains (OD) = vector sum of OC and OB.

$=\sqrt{\{(222{\cdot}2+444{\cdot}5)^2+(453{\cdot}4-166{\cdot}5)^2\}}$
$=726$ amps.

Hence, power-factor of the whole load

$$=\frac{444{\cdot}5+222{\cdot}2}{726}=\frac{666{\cdot}7}{726}=0{\cdot}92$$

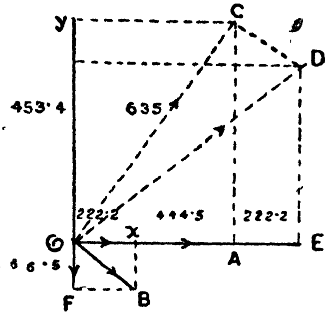


Fig. 3·27

Increase of loss in synchronous motor

$= (277{\cdot}7^2 - 222{\cdot}2^2) \times 0{\cdot}1$
$= 2{,}774$ watts.

Decrease of loss in transmission line

$= (806^2 - 726^2) \times 0{\cdot}06$
$= 7{,}353$ watts.

Net saving $= 7{,}353 - 2{,}774$
$= 4{,}579$ watts.

119. Line K. V. A. when power-factor is improved.

Let P_1 = power taken by the induction motor, kW.

Q_1 = reactive power taken by the induction motors, K. V. A.

$L = \sqrt{P_1^2 + Q_1^2}$ = total K.V.A. of the induction motors.

P_2 = true power taken by rotary condenser, kW.

Q_2 = reactive power taken by rotary condenser, K. V. A.

$K = \sqrt{P_2^2 + Q_2^2}$ = total K. V. A. of condenser.

Line K. V. A. $= \sqrt{(P_1 + P_2)^2 + (Q_2 - Q_1)^2}$.

120. Economical Limit of Power-Factor Correction :—It is not always advisable to increase the power-factor of a system to unity from the economical point of view, although it is desirable from the point of view of electrical operation. The maximum power-factor at which a system can be operated depends on the relative cost of generating and advancing plant.

Consider a system whose K. V. A is P, where the current lags behind the voltage by an angle ϕ_1, so that the power factor of the system is $\cos\phi_1$. Let the angle of lag be diminished to ϕ_2 and consequently the power factor increased to $\cos\phi_2$ by means of phase advancing apparatus. Then the increase of true power will be $P(\cos\phi_2 - \cos\phi_1)$. The wattless K. V. A. are reduced from $P\sin\phi_1$ to $P\sin\phi_2$, so that the capacity of the phase advancing apparatus should be

$$P(\sin\phi_1 - \sin\phi_2).$$

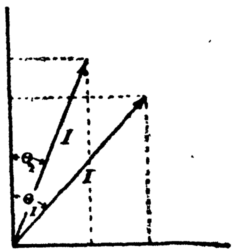
If the true power of the system were increased by the same amount by installing extra generating plant, the additional expenditure will be

$$\text{Rs. } aP(\cos\phi_2 - \cos\phi_1)$$

at a total cost of Rs. a per K. V. A.

If the true power were increased by installing phase advancing plant at a cost of Rs. b per K. V. A., the necessary expenditure will be Rs. $b\,P(\sin\phi_1 - \sin\phi_2)$.

Hence, for economical correction, the value of the new angle of lag ϕ_2 must be such that



3·28

$$b\,P(\sin\phi_1 - \sin\phi_2) < a\,P(\cos\phi_2 - \cos\phi_1)$$

$$\text{or, } \frac{b}{a} < \frac{\cos\phi_2 - \cos\phi_1}{\sin\phi_1 - \sin\phi_2}.$$

121. Angular Lag due to load

$\phi =$ the phase angle between E and I.

$E =$ the line or terminal voltage due per phase.

$e =$ induced or counter E. M. F. per phase: may be taken from no-load saturation curve for given excitation.

r=resistance of armature per phase.
x=synchronous reactance per phase.
I=current per phase.

For any load on a synchronous generator there is an angular advance of the generated E.M.F ahead of the terminal E.M.F. The phase displacement is accompanied by a shift in the synchronous position of the armature which may be calculated.

To calculate this angle α

$$e^2=(E-Ir\cos\phi-Ix\sin\phi)^2+(Ir\sin\phi-Ix\cos\phi)^2$$

$$\alpha=\sin^{-1}\left[\frac{(Ir\sin\phi-x\cos\phi)}{e}\right]$$

$$\text{or, } \sin\alpha=\frac{I\cos\phi}{\text{short-circuit currents}}.$$

The mechanical displacement of the armature for the load $E\,I\cos\phi$ per phase is $2\alpha/p$, where p is the number of poles.

122. Synchronising:—A synchronous motor is started, brought up to speed and e is made equal to E_g. When e and E_g are in opposite directions, the switch s is closed and the load is put on the motor. This is called synchronising.

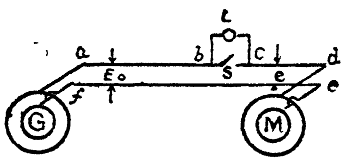


Fig. 3·29

123. Synchronising Torque.—This is the synchronising power of the motor and is a measure of its ability to keep in step with its supply circuit. It may be expressed in terms of torque per degree of displacement.

Let P=kW. output of the motor.

α=the angular displacement of the armature in electrical degrees for this load.

$$\text{Motor torque}=\frac{33{,}000\text{ kW.}}{0\cdot746\times2\pi\times\text{R. P. M.}}=\frac{7{,}050\times(\text{kW.})}{\text{R. P. M.}}$$

$$sin\ a = \frac{I\ r\ sin\ \phi - I\ x\ cos\ \phi}{e}$$

$$\text{Synchronising torque} = \frac{7{,}050 \times (\text{kW.})}{a \times (\text{R. P. M.})}$$

A high resistance between machines reduces the synchronising torque as it reduces *E*. A reactance between machines is not as bad as resistance. Increasing the excitation increases *e* and improves the synchronising torque.

124. Hunting :—The frequency of the E.M.F. of engine-driven alternators rises and falls regularly, if the angular velocity of the prime mover consists of a uniform angular velocity with a superimposed oscillation.

If such an E. M. F. is applied to a synchronous motor, the synchronous speed of the motor tends to rise and fall regularly with the frequency and the motor tends to have a superimposed oscillation similar to that of an alternator. If the natural period of oscillation of the motor has the same frequency as this forced oscillation, the effect will be cumulative, and the motor will oscillate considerably.

Boucherot and Kapp have shown that the natural period of any synchronous machine expressed in seconds or fraction of a second is given by the formula

$$T = 0{\cdot}308\ N \sqrt{\frac{Wk^2.}{f\ g\ m\ E\ I_o.}}$$

where, N = R. P. M. of revolving part.
W = total weight of revolving part including any fly-wheel in pounds.
k = radius of gyration of W in feet.
f = frequency of current, cycles in second.
g = acceleration of gravity, in feet per sec. per sec. = 32 2.
M = number of phases.
E = terminal voltage per phase
I_o = short-circuit current of machine per phase and at excitation used.

The frequency of the natural period expressed in impulses per minute is $f = 60/T$.

The formula shows that the greater the fly-wheel effect kW^2, the longer will be the periodic time of a swing. The greater the short-circuit current or excitation, the shorter will be the periodic time. The periodic time may be increased by connecting reactance coils in series with the machine between its terminals and the busbars.

If T_0 is the periodic time of any other pulsating force in the system, as the stroke of a steam engine, the danger of hunting is greatest when $T/T_0 = \frac{1}{4}, \frac{1}{3}, \frac{1}{2}, 1, 3, 5,$ etc.

In practice, the maximum output for a given voltage is only reached under two conditions (1) when due to extraneous cause the line voltage decreases to a fractional value, the maximum value decreases as the square of the voltage ; (2) when due to hunting or pulsation, the flow of energy into or out of the machine reaches excessive values momentarily. In one of these swings the power may reach the value of maximum output or exceed it and the machine shut down. Although the power of the machine drops off gradually after the point of maximum output is reached, the motor is unstable in this region and is more than likely to shut down, when the condition is reached.

Remedy :—Apply the same remedies as in the case of alternator.

(1) Dampen the governor, if the impressed oscillations are due to a hunting governor.

(2) Fit a heavier fly wheel to change the natural period of vibration.

(3) Dampen the oscillations electrically by the use of pole dampers.

(4) A tendency to hunt is damped by solid pole pieces or bridges between poles.

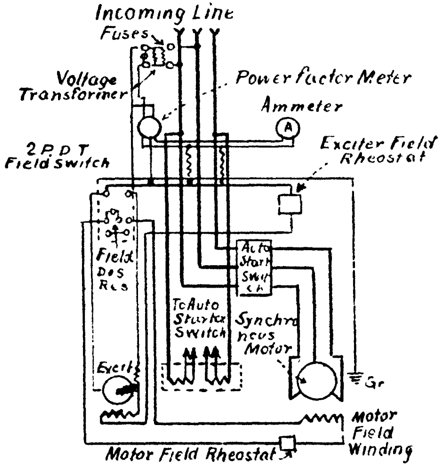
125. To Start a Synchronous Motor—The steps are as follows .—

(1) See that the motor is clean, that the bearings have plenty of oil, with the oil rings free to turn.

(2) See that all switches are open.

(3) Close the double-throw field switch, cutting in the field rheostat with its resistance all in.

(4) Close the main-line switch (if any), and throw the double-throw switch in the *starting* position. See that the motor speeds up to synchronism in, from 30 to 60 secs.



Connections of a Self-Starting Synchronous Motor.
Fig. 3·30

(5) When the motor is up to speed, throw the field switch over to the *running* position with rheostat all in.

(6) Throw the double-throw main switch over to *running* position, putting the motor on full-line voltage.

(7) Adjust field rheostat for minimum armature current. The connections of a three-phase, self-starting synchronous motor to its exciter are shown in Fig. 3·30. A double-throw switch is inserted in the field circuit. This may (where the exciter is connected to the shaft of the synchronous motor) be a single-throw switch and the field connected direct from the exciter armature to the rheostat in the circuit. The field thus remains inactive and is gradually excited as the motor speeds up.

126. Difficulties in Starting Synchronous Motors.—As a rule, synchronous motors are weaker in starting than are induction motors This counts as a serious drawback of the motors of this class In general, however, a synchronous motor will start itself and, perhaps, with a very light load. No field current is necessary for starting, as the flux which tends to start the motor is not the flux that operates it for running it up to its proper speed In starting, the field current is lagging, and as such it tends to lower the voltage on the supply mains, or the applied voltage. As in induction motors the starting torque is proportional to the square of the applied voltage, *e.g.*, for half the voltage, the starting effort is quartered. If a synchronous motor does not start, the cause may be that the voltage on the line has been sufficiently lowered below the value necessary for starting.

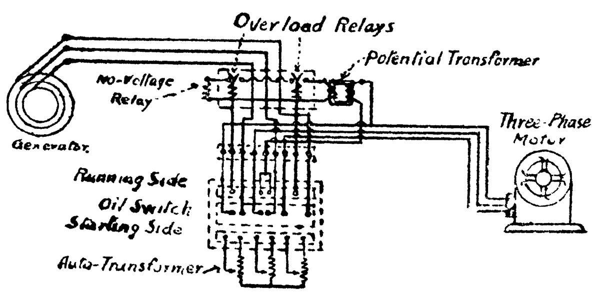
As a general rule, at least half the voltage is required for starting a synchronous motor. Difficulty in starting may also arise from an open circuit in one of the lines to the motor. For example, in the case of a three-phase motor, if one of the lines is open, the motor becomes single-phase, and a single-phase synchronous motor is not self-starting. The motor will thus fail to start and will soon get hot. The same is true of a two-phase motor, if one of the phases remains open.

Trouble in starting may also arise from a rather slight increase in static friction For example, the bearings may be too tight,—perhaps, from cutting during the previous run; or the belt tension may be too much—in case the motor is belted to its load ; or any cause, which increases starting friction, will probably give trouble.

Failure in starting may again be caused by field excitation being on the motor, as above referred to. After excitation exceeds one-quarter normal value, the starting torque is influenced. With full field on, most synchronous motors will not start at all.

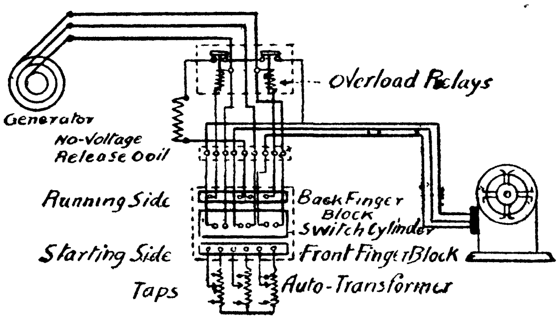
If the proper voltage is applied to a motor, and all the circuits are closed except the field circuit, and the friction is a minimum, and still the motor fails to start,

the fault is probably with the manufacturer. Pole pieces are sometimes provided with extra starting windings or conducting bridges to assist in starting. The manufacturer in shipping may have possibly omitted these devices. In such a case reference should be made to the factory. In most cases compensators are used for starting synchronous motors. If there is a reversed phase in the compensator, or, a wrong connection in the windings of the armature of the motor, there will be very little starting torque A wrong connection can be located by noting the unbalanced entering currents. This should be done with the armature revolving slowly The revolving can be effected by any mechanical means Even with correct connections, the armature currents of the three phases will usually differ somewhat when the motor is standing still. This is due to the position of the poles relative to the armature. But when the armature is revolving slowly, the currents should average up. In case the rotor cannot be revolved by mechanical means, similar points on each phase of the armature must be found out. Then, if the rotor is set successively at these points, the currents in the phases at each setting should be the same. Each phase, when located in a certain specific position in relation to a pole, should, with right connections, take a certain specific current. With wrong connections, the currents will differ.



Potential Transformer for No-Voltage Relay on a High-Voltage Motor.
Fig. 3'31

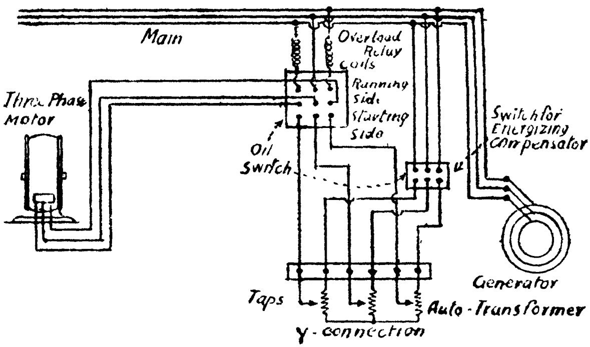
127. When no-voltage release compensator starters are used for high-voltage motors, a small voltage transformer is usually arranged, as in Fig. 3·31, to energise the no-voltage coil. This arrangement is used by certain manufacturers for compensators, with the no-voltage release attachment, for voltages of from 1,040 to 2,500. The secondary of the transformer furnishes 110 volts for which the no-voltage relay is wound.



Overload Relays on Two-Phase Starting Compensator.

Fig. 3·32

128. Overload release coils on compensators are arranged essentially as shown in Figs. 3·31 and 3·32. When there is an overload on either phase, the iron plunger of the overload relay is drawn up which opens the no-voltage release-coil, circuit. This de-energises the no-voltage release coil and the compensator circuit is automatically opened, as described in the paragraph on the no-voltage release. The overload relays are usually arranged, so that they can be adjusted to operate at different currents just as a circuit breaker can be adjusted. An inverse-time-element feature is usually incorporated, whereby the relay will operate almost insatntly on very heavy overloads, but will not operate until a certain interval of time has elapsed (the length of the interval being approximately inversely proportional to the amount of overload) on lesser



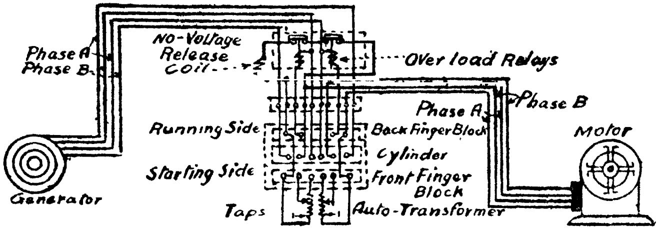
Starting Compensator with Separate Switches and Auto-Transformer for High-Voltage or Large Capacity Motor.

Fig. 3'33

foverloads. It will be noted from the diagrams that fuses are not necessary where the overload relays are used. A decided advantage of the overload relays is that they can be adjusted to protect a motor against running, single-phase. If one phase opens, sufficient additional current will be drawn through the outers to operate a relay which will open the circuit to the compensator. An installation of a Westinghouse compensator having no-voltage and overload relays is shown in Fig. 3'33.

***129 A no-voltage release can be provided on starting compensators.** The connection diagram is shown in Fig. 3'34 ; for a three-phase compensator it is similar. When a condition of no-voltage exists on the line, the no-voltage release coil is de-energised, which permits the iron armature or core of the no-voltage coil to drop, which automatically releases the compensator handle, which is returned to the off position by its spring. This opens the circuit through the compensator.

* T. Croft's American Electrician's Handbook



Overload Release Coils on Three-Phase Starting Compensator.
Fig. 3·34

Induction Motor

130. Elementary Theory of Polyphase Induction Motor:—Hold a horse-shoe magnet over a compass needle. The needle takes the position parallel to the lines of force which flow from one pole to the other. Rotate the magnet and the needle will follow.

Substitute a four-pole electromagnet for the horse-shoe magnet and let the current flow about, either one of the sets of poles separately, and place the needle over a pair of poles, the needle will take its position parallel to the lines of force that may be flowing from one pole to the other.

Excite the two sets of poles at the same time by current of equal strength, then the needle will take its position diagonally, half-way between the two sets of poles.

If now one of these currents is growing stronger while the other is becoming weaker, the needle will be attracted towards the former until it reaches the maximum value; when, if the currents are alternating, the strong current having reached its maximum begins to weaken, and the other current, having not only reversed its directions but begun to grow strong, attracts the needle away from the first current and in the same direction of rotation. Repeat the process several times, the needle will continue to revolve and its direction of rotation

will be determined by the phase relation of the two currents, and the direction of rotation can be reversed by reversing the leads of one phase.

Now replace the compass needle by an iron core wound with copper conductors ; secondary currents will be induced in these windings, which will react on the field windings, and rotation will be produced in the core just as it was in the case of the compass needle.

Thus the current, in the conductors of one phase, magnetises poles C and D, and that the other phase, the poles A and B. The arrangement of the winding is such that a current entering at C will, at a given instant, produce a south pole at C and a north pole at D, Fig. 3·35.

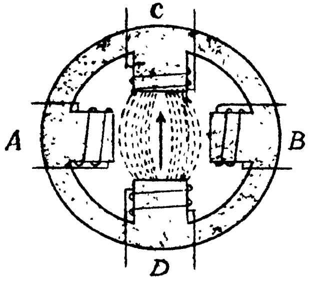


Fig. 3·35

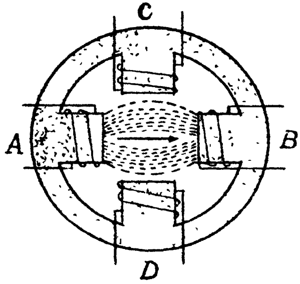


Fig. 3·36

At one instant the motor poles C and D are magnetised, while poles A and B are not. Hence, the iron rotor wound, with copper conductors, will assume the vertical position, as shown in Figure 3·35.

At another later instant, represented by Fig 3·37, the currents in both the phases are equal and in the same direction; the motor poles will be magnetised, as shown, and the rotor will be drawn into the position indicated. At the instant illustrated by Fig. 3·36, because of the properties of two-phase currents, there is no current in the phase, the conductors of which

are wound on poles C and D, but the current in the phase, the conductors of which magnetise poles A and B, is a maximum.

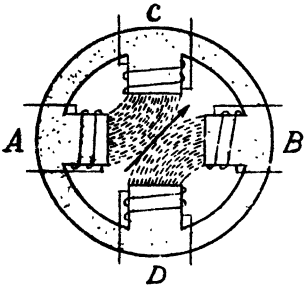


Fig. 3·37

Hence, the rotor is now drawn into a horizontal position. Similar action occurs during successive instants, and the rotor will be caused to rotate in the same direction within the motor frame, so long as the two-phase current is applied to the motor terminals.

The rotating magnetic field rotates within the motor frame and drags the rotor around with it.

The magnetic attraction or drag exerted on the rotor in a simple motor, built as explained, would be pulsating in effect ; hence, the torque exerted by such a motor would not be uniform. Hence, in order to rotate the rotor in one direction, a quadrature relationship in both time and space between the two sets of poles, as in the case of a two-phase system, is necessary. The resulting flux acting on this armature forms the well-known rotating magnetic field.

The induction motors may be classed as polyphase or single-phase induction motors. The action of a polyphase induction motor may be likened to that of a direct-current motor, in which both the fields and the armature are capable of rotation. Supposing the fields of such a motor to be fully excited and rotate with the armature at rest and short-circuited, a current of any desired magnitude may be induced in the armature, since the generation of a current depends simply on the relative motion of the fields and the armature.

In the **single-phase induction motor** there is an inductive action between the field and the armature, similar to that which takes place in a polyphase induction motor ; the field, however, is not a simple rotating field, but may be regarded as two fields rotating in

opposite directions. The result of this is that at starting the armature is subject to an equal pull in both directions; in other words, the motor will not start by itself. But, when once the armature has been started in either direction, the torque in that direction increases, while that in the opposite direction decreases. As a result, the motor works as an induction machine at a speed just below synchronism similarly to the polyphase motor. This type of induction motor, therefore, needs some special starting device.

131. Maximum Load :—As the load increases, the speed slightly decreases, until the maximum load is reached. If the load be increased beyond this, the motor is brought to a standstill. In practice, the working load should not exceed 50 to 60 per cent. of the maximum load.

132. Speed Regulation :—If resistance be placed in the circuit of the rotor so as to increase the total resistance, say, to double its value, the slip for equal torque will be double what it was with the original resistance. Thus with any load not greater than the maximum, any required speed can be obtained by merely altering the rotor resistance. This is a wasteful method of speed regulation, and various methods are in use for obtaining economical speed control. These include :—

(1) Changing the number of poles, with or without change in the number of phases.
(2) Cascade connection with one or more motors.
(3) Addition of variable-speed set.

133. Rotating Flux.—The currents in the two sets of coils, AB and CD, may be taken to cause the rotating magnetic field. The current in phase AB sets up an alternating flux through the armature in the horizontal direction, while that of phase CD sets up a similar flux in the vertical direction. These fluxes have space relationship at right angles to each other.

The time relationship of the fluxes is shown by their equations.

Thus

$$\phi_1 = \phi_m \sin \omega t.$$

$$\phi_2 = \phi_m \sin (\omega t - \pi/2$$

Thus in the two-phase induction motor a revolving field is produced by the combination of space-phase and time-phase factors, as determined by the relative space positions on the motor windings and the conditions of the circuit from which the power is derived.

The resultant will then be composed of a horizontal component having the value of ϕ_A at that instant, and a vertical component ϕ_B at the same instant. This may be expressed as

$$\phi = \phi_1 + j\,\phi_2 = \phi_m\,(sin\ \omega t - cos\ \omega t).$$

If the vectors are plotted through 360°, the locus of the ends of the resultant flux vectors is a circle of radius ϕ_m, and the speed of rotation of the flux is f, the frequency of the alternating current.

134 Rotating Field by Three-Phase Current.—In the three-phase stator the coils in the three windings carry currents differing in phase by 120°. Some care is necessary to ensure that they are connected in the right sense so that the direction of the three magnetising forces in the rotor space may be such as to produce the desired rotation.

Note that the poles of an induction motor do not really project from the rest of the stator.

135. Elements of Induction Motor.—The primary of an induction motor means that part which receives energy and has direct connection to the source of electric energy, the other member is called the secondary.

Stator.—The member of an induction motor which remains stationary, whether it be primary or secondary, is called the stator.

In most machines the primary is the stator.

The Rotor.—The revolving member is called the rotor. It consists of grooved cylinder of laminated steel mounted on a spider. The conductors lie in grooves in the steel core and *the nature of the rotor winding largely determines the type of motor.* In order to keep the magnetic reluctance as low as possible

the air-gap between the stator and rotor must be minimum, consistent with safe clearance. For this reason the shaft is extra stiff and the bearings comparatively large.

The secondary may be wound on the rotor in much the same way as the armature of a direct-current motor or similar to those on the stator when it is called the slip-ring or wound rotor, the other type being called the squirrel-cage motor.

Both two- and three-phase motors are generally provided with three-phase rotors, so that the starting, described for three-phase motors, will usually be equally well for two-phase motors.

Wound Rotor.—In this the terminals brought out to slip rings are mounted on the shaft. The rotor winding is connected to an external rheostat, through the slip rings, by means of which the resistance in the rotor circuit may be varied.

The rheostat for regulating the resistance of the rotor circuit is sometimes placed in the rotor structure of small rotors, where no rings are required, but a rod used to change the resistance of the rotor circuit projects through the hollow shaft.

There is no connection between line supply and the current in the rotor circuit *Load conditions determine the choice* between wound rotor and squirrel-cage types of induction motor.

Wound rotors or slip-ring motors have a large starting torque, and take less current from the line, and are used where the starting load is very heavy and where the effect of large starting current and low power factor are undesirable, and where variable speed below the normal, although at the cost of efficiency, is required.

Examples of use.—Rolling mills, large presses, hoists and lifts.

It is more costly than the other type. But for tools having a large starting torque this type must be used.

By means of a variable resistance inserted in the armature circuit the maximum starting torque can be made available from standstill up to full-speed.

Squirrel-Cage Rotor —In the rotor of this type the conductors are straight bars of copper all connected together at each end of the rotor by copper rings, called the squirrel-cage rotor, since the conductors are connected in parallel ; the resistance of such a winding is small. This type is the most simple and reliable motor made ; it is extremely free from break-down such as commutator motors are subject to, and operates at higher temperature for short periods without danger. It takes heavy starting currents and is started by inserting resistance in the line circuit or by using autotransformer which reduces the voltage at the motor terminals, so it cannot be started under heavy load. It has a fair starting torque and a constant speed which cannot be adjusted more than the extent of about 5 per cent. when the loads vary. A fairly good starting torque can be secured by making the rotor bars of greater length and of some material, such as brass, having a higher resistance than copper. The end connection may also be made of high resistance This, however, occasions a constant loss owing to the insertion of resistance and as such is not very efficient. The more the resistance in the secondary, the greater the speed reduction and the less the efficiency.

Sometimes the rotor of the squirrel-cage motor exhibits a tendency to remain in one place and not to rotate at all, when the number of rotor and stator slots have a common factor. In such a case there will be certain rotor positions which make the air gap reluctance a minimum and it is in such positions that the rotor tends to remain. The remedy is to make the number of rotor slots prime to the number of stator slots, a point well-known in design, known as the magnetic locking.

It is less costly than the wound-rotor type and as such is used in all cases where the load conditions fall within the torque speed limitations.

136 Transformer Features of Polyphase Motors —The induction motor may be treated as a transformer or it may be considered a special form of

alternating current generator, delivering current to a fictitious resistance as a load. It may be assumed that its torque is due to the current produced in the secondary of the transformer of one phase, acting upon the magnetism due to the primary of another phase ; or it is possible to consider that the magnetisms due to the separate phases combine to produce a revolving field in which the secondary circuits are placed.

The magnetic field passing between the primary and secondary windings of a transformer produces mechanical forces tending to push the coils apart. In the potential transformer the two windings are rigidly fixed in position, and hence, although the forces exist, no motion is produced and no energy is changed into the mechanical form On short-circuits, with excessive currents flowing, these forces may tear the transformers to pieces. In the constant-current transformes the secondary winding is, to a certain extent, movable, and the reaction between the two fields furnishes the means for automatic regulation. In the induction motor the windings of the successive phases are so arranged in speed, around a rotating spider, that a continuous torque is produced in one direction. Like the transformer, the induction motor has a primary and a secondary. Either may be placed on the rotating spider, but, as the outside offers more space, it is generally desirable to wind the primary with the highest voltage on the stationary drum or stator, and place the secondary, low-voltage winding, in the rotating spider, or rotor.

If we insert in the secondary a resistance, like the load resistance in the secondary of the transformer, sufficient to consume the same power, as the mechanical load, the circuits for the induction motor are the same as for the transformer.

The magnetising current is much larger in the induction motor than in a transformer of like capacity, due to the larger leakage flux caused by the air gap in the magnetic circuit. The component taken by the conductance represents the part supplying the core losses, and is in time phase with the voltage, while the

exciting current is in time quadrature with the voltage. The secondary reactance is proportional to the frequency of the secondary current, hence to the slip, and it, therefore, varies with the load. As the slip, under operating conditions of squirrel-cage induction motors, is only a small per cent. of the speed, the reactance of the secondary is necessarily small, as compared to the reactance of the primary.

137. Slip.—The speed of the rotor is always less than the speed of the rotating magnetic field, because the conductors of the secondary must cut the lines of force of the field in order to produce current in the secondary winding, and pull the rotor around ; if the speeds were identical, there would be no cutting.

'Slip' is defined as the ratio of the difference of the synchronous speed and the rotor speed, or actual speed to the synchronous speed, and is often given in percentage of the synchronous velocity of the machine.

This is considered in terms of the synchronous speed ; that is to say, if the synchronous speed were 1,500 R. P. M. and the actual speed of the rotor or secondary member were 1,470 R. P. M., the slip would be $30 \div 1{,}500 = 0{\cdot}02$, *i e.*, 2 per cent. It is the ratio of copper loss of secondary to total secondary input.

Example 12. A twelve-pole motor is supplied at a frequency of 50, and the speed of the rotor under a certain load is observed to be 490 : determine the slip.

Solution.—

Synchronous speed $= 2 \times 50 \times 60/12 = 500$ R. P. M.

$\therefore$ Slip $= (500 - 490)/500 = {\cdot}02$, or 2 per cent.

The frequency of the induced secondary current (*i.e.*, the rotor current in the motor) as usually arranged in the same percentage of the supply frequency as the slip is of the synchronous speed, *e.g.*, if the rotor runs with 4 per cent. slip and the supply frequency is 50 cycles/sec., the rotor current is 4 % of 50 or 2 cycles/second.

The energy of the "slip current" in the secondary of an induction motor is dissipated in the form of I^2R, heat in the rotor windings and external resistance if any,

but this energy can be utilised in auxiliary machines. Normally, its frequency and voltage are very low; but if the auxiliary machine is used to effect speed control, the frequency of the rotor current is increased as the speed of the machine is decreased.

138. The Most Accurate and Convenient Method of Determining Slip.—If I_2 be any observed value of secondary current, and R_2 the secondary resistance and W the output of the motor, then

$$\text{the slip } s = \frac{I_2^2 R_2}{W + I_2^2 R_2} = \frac{\text{copper loss of secondary}}{\text{total secondary input}}.$$

To prove this, consider the magnetism cut by the secondary windings to be of a strength which would cause to be generated E_2 volts in the windings at 100 per cent. slip

Let s be any given slip, W_s the total secondary watts, θ the angle of lag of secondary current and X_2 the secondary reactance at 100 per cent. slip, then

$$\frac{I_2^2 R_2}{W + I^2 R_2} = \frac{I_2^2 R_2}{W_s} = \frac{I_2^2 R_2}{I_2 E_2 \cos\theta}$$

$$I_2 = \frac{s E_2}{\sqrt{R_2^2 + X_2^2 S^2}} = \frac{s E_2}{R_2 \sec\theta}$$

$$\text{and } \frac{I_2^2 R_2}{I_2 E_2 \cos\theta} = \frac{s I_2 E_2 R_2}{I_2 E_2 R_2 \cos\theta \sec\theta} = s$$

Since neither E_2 nor X_2 appears in the above equation, the relation is independent of the strength of field magnetism cut by the secondary windings and of the secondary reactance.

* **139. (a) The Stroboscopic Method of Determination of Slip**.—On the end of the shaft or the pulley, mark as many equally-spaced radial lines as there are pairs of poles on the motor, and illuminate these lines by means of an arc lamp connected to the circuit from which the

* J. F. Wilson's Essentials of Electrical Engineering

motor receives its current. When the motor is in operation, the radial lines appear to rotate in a direction opposite to that of the rotor. The speed of this apparent rotation is proportional to the slip of the rotor.

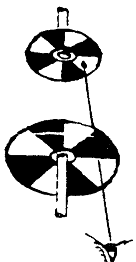


Fig. 3·38

This method of slip measurement depends on the fact that the light from an alternating-current arc lamp is pulsating If the rotor moved at synchronous speed, the radial lines would advance through the angular distance of one pole pitch for each pulsation of the light, and successive pulsations would show the lines in the same relative positions. But the angular advance of the lines is less than the angular pitch of the poles, and each successive pulsation of the light shows the lines in a position slightly behind that which it occupied at the previous pulsation.

Example 13 A four-pole induction motor is operated from 50-cycle supply mains. Determine the slip of its rotor when 100 radial lines pass through the field of vision in one minute.

Solution :—

$100 \times 100/50 \times 60 \times 2 = 1·66$ per cent.

Fig. 3·38 shows another method.

where, if n = number of passages of the sectors,

n_s = number of sectors,

n_r = number of revolutions recorded during the interval under observation.

Then $(n/n_s(/n_r$=slip in terms of V.

(b) The Voltmeter Method of Determination of Slip—Another simple method for the determination of slip is to connect a contact maker to the shaft of the motor so that it closes, once in each revolution of the rotor, the circuit of a voltmeter connected across the mains supplying the motor. The voltmeter pointer swings back and forth, the rate of the swing being

proportional to the slip of the motor. If an electrodynamometer type of voltmeter is used, the rate at which the pointer swings is twice as great as if the voltmeter is of the permanent magnet type.

140. The relation between speed, frequency and number of poles of an alternating current motor of the Synchronous or Induction type.

$$n = 120 \times f \times (1{\cdot}00 - s)/p \qquad \text{(speed)},$$
$$f = p \times n / \left\{ 120 \times (1{\cdot}00 - s) \right\} \qquad \text{(frequency)},$$
$$s = 1{\cdot}00 - p \times n / 120 \times f \qquad \text{(slip)},$$
$$p = 120 \times f \times (1{\cdot}00 - s)/n,$$

where,

n = revolutions per minute of the rotor,
f = frequency in cycles per second,
p = number of poles,
s = slip.

If an induction motor be driven mechanically, by an overtaking load or otherwise, at higher than its synchronous speed, it operates as an asynchronous alternator and returns energy to the *A. C.* supply mains, thus regenerative breaking is effected.

141. Complete Performance Diagram of the Polyphase Induction Motor. Experimental Determination of the Circle Diagram.—Complete the connections as shown in Fig. 3·39. The motor is supplied with current and run light on normal voltage and frequency. Measure the current, voltage, and watts per phase.

At no-load I_{exc} per phase is the ammeter reading. The power input is the sum of the wattmeter readings in the two positions, *i.e.*,

$$p_1 + p_2 = \sqrt{3}.E\, I_{exc} \cos \phi.$$

∴ the angle by which I_{exc} lags behind the impressed E. M. F is $\phi = \cos^{-1}(p_1+p_2)/\sqrt{3}\, E_1\, I_{exc}$. where E_1 is the voltmeter reading. The exciting current per phase is now completely determined, and may be drawn to a convenient scale.

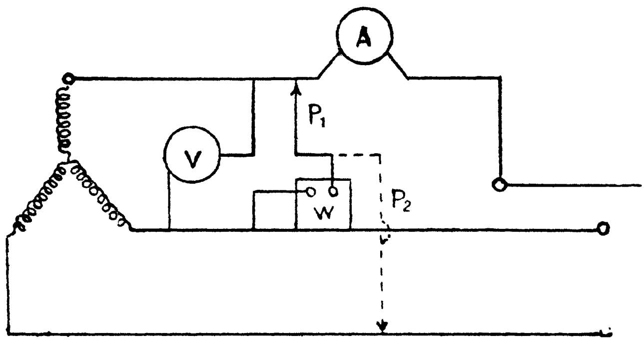


Fig. 3·39

From the readings thus obtained the power factor at no-load is readily determined. For, when its rotor is unconnected with any external load, *at no-load*, the rated voltage is applied to the terminals and readings taken of current and power input The ammeter gives the magnetising current ; and the wattmeter gives the core, windage and the friction losses. The losses due to windage and friction are small ; so the power indicated by the wattmeter may be considered as due to conductance in the magnetising circuit. The magnetising current has, therefore, components in time phase and time quadrature with the voltage, and their magnitudes are determined by the amperes, volts and watts taken at no-load. In the Fig. 3·40 the vector ME represents the applied voltage per phase. MO represents the no-load current, set off such that the cosine of the angle $EMO =$ power factor of the motor running light The energy component of this is NM, which equals the no-load watts per phase divided by the applied $P.D.$ NM is assumed constant.

At Standstill :—For the second set of reading *the rotor is clamped*, and sufficient voltage, less than that at which the motor is rated, is applied to give about twice the full-load current in the primary. The impressed voltage with the rotor locked should be reduced to such a value

as will send a current which will produce the same heating in the windings as does continuous full-load operation. Readings are taken to obtain the volts, amperes and watts. At standstill the rotor current is very nearly directly proportional to the impressed voltage; and hence, the value of the equivalent current in the primary at the rated voltage of the motor is found by multiplying the observed value by the voltage ratio. That is, OF is the current that would be due to full pressure; but as this current would be very large and would over-heat the windings, it is usual to calculate it from a smaller current obtained when a reduced voltage is applied. This reduced voltage is 20 to 25 per cent. of the supply voltage to give about twice the full-load current in the primary and the short-circuit current OF at the line or supply voltage

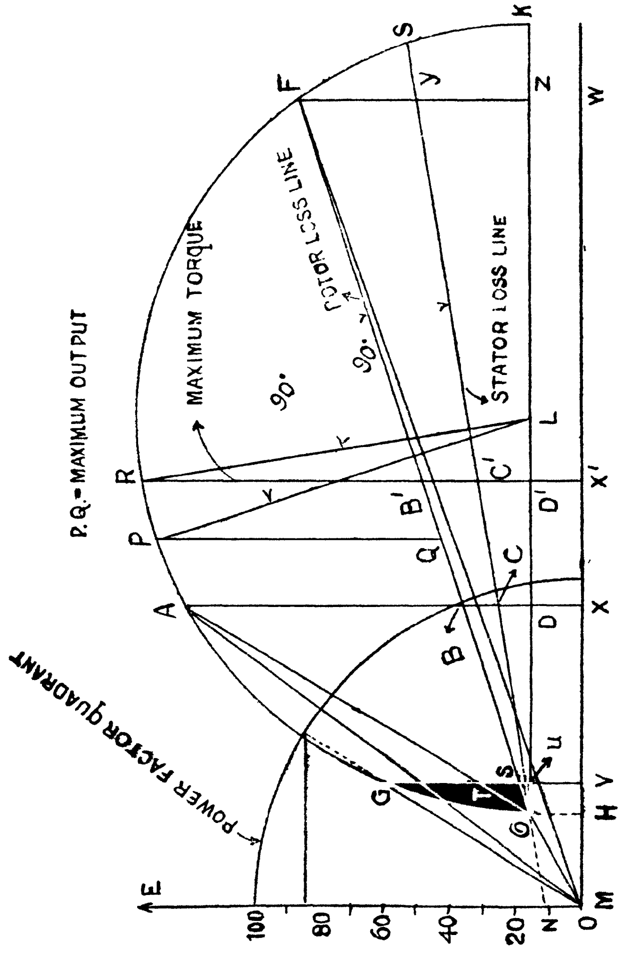
$$= \left.\begin{array}{l}\text{short-circuit current}\\ \text{observed on test with}\\ \text{reduced voltage}\end{array}\right\} \times \frac{\text{line volts}}{\text{voltage employed on test}}$$

When performing the above test on slip-ring motors, the rotor slip rings must be short-circuited, just as they are when the machine is running on load.

Several such values should be taken and a curve drawn connecting applied P. D. per phase and short-circuit current per phase Owing to excessive heating, it will be sufficient to take a value of applied voltage which will send twice full-load current through the machine. The relation between current and voltage is a linear one till saturation of the iron part of the leakage path takes place. The value of the short-circuit current for normal applied voltage is obtained from the curve, assuming a linear relation. This value MF is set off at the angle FME, which is equal to the angle of lag at short-circuit.

The current locus is primarily based on the transformer feature of the induction motor. It is not accurate only to the extent to which the motor differs from a transformer in electrical behaviour. The friction loss is treated as a core loss, and hence, it is tacitly assumed that this loss necessitates a power component of current in only the primary winding. This treatment involves

no error in the primary current, but it neglects a certain component of secondary current, which, however, is too small to need consideration.



Circle Diagram of Induction Motor.
Fig. 3·40

Geometrical Construction.—Draw NK horizontally, as shown. Then our circle must pass through O and F, and have its centre on OK Bisect OF and draw a perpendicular to OF to intersect NK in L Then L is the centre of our circle.

Join FM and draw FZ perpendicular to NK.

Make $YZ = OF^2 \times R_s/E$, or more accurately $= R (I_2^2 - I_1^2)$ or FY/YZ = secondary to primary copper losses.

Where R_s = stator resistance per phase.

I_2 = the stator current with the rotor blocked ;

I_1 = stator current at no-load

Then $E \times FY$ gives us the loss in the rotor at standstill per phase.

Owing to the uncertainty of the value of the current at standstill a certain amount of error is possible by this method.

At a point A on this locus, the line MA represents the primary current, while the angle EMA is the angle of lag of the current behind the primary E. M F, EM. The line OA shows the secondary current, both in value and phase position. When the secondary current has zero value, that is, at *synchronous speed*, the primary current becomes equal to MO, ON being its " wattless " component and NM its power component to supply all of the no-load losses

When the rotor is stationary, the secondary current assumes some value such as OF, and the primary current MF is the vector sum of OF and OM The curve, OAF, is the arc of a circle having its centre on the line NO prolonged.

Under starting conditions all of the power received by the motor is used in supplying the copper and core losses of the machine. The line FW is the power component of the primary current at starting, and hence, *by the use of the proper scale*, it may represent the total losses of the machine when the rotor is stationary. The line $ZF = (FW - MN)$, which shows the secondary copper loss and the increase of the primary copper loss

over its (synchronous) no-load value. The line FZ being properly divided at Y, YZ represents the increases of the primary copper loss, and YF the secondary copper loss for the current OF. By drawing from the point O a straight line, OYS, passing through the point Y, the complete performance of the machine may be determined directly from inspection.

If from any point A on the circular locus a line be drawn perpendicular to the diameter, OK, the following quantities may be observed at once:—

MA is the primary current.
EMA is the primary angle of lag
$\cos EMA$ is the power factor
OA is the secondary current.
AX is the total primary input, $\therefore nE_1\ (AX)$=input in watts
XD is the "constant" losses of the machine, $\therefore nE_1 \times (XD)$=core loss, windage and friction in watts.
CD is the added primary copper loss, $\therefore nE_1\ (CD)$ =primary copper losses in watts.
CX is the total primary losses, $\therefore nE_1\ (CX)$ =total primary losses in watts.
AC is the total secondary input in watts, $\therefore nE_1 (AC)$ =total secondary input in watts.
AB is the torque in synchronous watts.
BC is the secondary copper loss, $\therefore nE_1\ (BC)$ =secondary copper loss.
$BC \div AC$=the slip.
BA is the output, $\therefore nE_1\ (BA)$=output in watts or mechanical load.
$BA \div AC$ is the speed.
$BA \div AX$ is the efficiency.
Maximum torque$=nE_1\ (RC')$.
Maximum output$=n\ E_1\ (PQ)$.

If the above quantities in the circle diagram represent values per phase, the corresponding quantities for motor should be multiplied by n, the number of phases.

Power factor$=\cos EMA=AX/AM$

Torque (in Kg at one metre radius)

$$=\frac{n\,E_1\ (AB)}{2\ \pi\ (9{\cdot}806)\ (\text{R.P.M.})}$$

Torque (in lbs. at 1 ft. radius)

$$=\frac{n\,E_1\ (AB)\ 33{,}000}{2\ \pi\ (746)\ \text{R.P.M.}}$$

Rotor torque in lbs. at 1 ft. radius is $T=7{\cdot}04\ W_s/$ synchronous speed.

A convenient way of expressing torque is in terms of synchronous watts or synchronous horse-power, which is the power that is developed by the torque at synchronous speed.

Torque in synchronous watts $=nE_1(AC)$.

Torque in synchronous horse-power $=nE_1(AC)/746$.

The MAXIMUM POWER FACTOR occurs when the point A is at G where the line MA or the current vector becomes tangent to the circle.

The MAXIMUM OUTPUT occurs when A is at P, the point of tangency of a line drawn parallel to OF, *i.e.*, when the current is of such a value that a line, drawn through the end of the current vector and tangent to the circle is parallel to OF.

The MAXIMUM TORQUE occurs when P is at R, the point of tangency of a line drawn parallel to OY. That is, when the current is of such a value that a line, drawn through the end of the current vector and tangent to the circle, is parallel to OY. The current, which is required to give maximum torque, varies somewhat with the primary resistance, but it is independent of the secondary resistance, although the speed at which the maximum torque is obtained depends largely on the value of the secondary resistance. The secondary resistance required to give maximum torque at starting bears to the assumed constant primary resistance the ratio of CR to $C'D'$ of Fig 3·40.

Denoting as α, the angle AOK, it will be seen that $OD = OA \cos \alpha$, and that $OA = OK \cos \alpha$. Hence, $OD = OK \cos^2 \alpha$, or $OD = OA^2 \div OK$. The interpretation of the last equation is that, as the point A moves around the circle, the line OD is, at all times, proportional to the square of the line OA. That is to say, the line OD is proportional to the secondary copper loss or to the increase in the primary copper loss over its no-load value. Under starting conditions, the secondary and the added primary copper losses are represented by FY and YZ; and at any point P, the corresponding losses must bear to FY and to YZ the ratio of OD to OZ Therefore, the secondary and the added primary copper losses are accurately shown by the lines BC and CD, respectively.

As the ratio of the secondary input is known, both the speed and the torque may be ascertained with precision. It is seen, therefore, that any errors introduced must relate to either the currents or the losses.

If the points O and F are obtained from an actual test on a machine, it is evident that the circle diagram, as constructed, must be at least approximately correct for the primary current locus. Under starting conditions the power received by the machine is accurately represented by FW. If the distance YZ be drawn equal to the easily-determined "added" primary copper loss, the distance YF must represent the secondary copper loss with a fair degree of accuracy.

It is especially worthy of note that under starting conditions and at synchronous speed the errors are eliminated, and throughout the operating range of the motor the various errors tend to cancel each other. Even in extreme cases, where the (synchronous) no-load triangle OMN is large in comparison with the circle diagram, the errors are relatively small, and, for most practical purposes, may well be neglected.

142. The principal advantage to be found in the graphical method of treating induction motor phenomena resides in the fact, that by the use

of a simple diagram one is able to follow optically, and thus mentally, the changes which take place throughout the operation of the machine, and is intended for students desiring a general understanding of the relations; while in the manipulation of algebraic formulæ, which must be used for absolute accuracy, one is apt to find himself more or less in the dark concerning these changes.

The method is simple and sufficiently accurate for commercial purposes. The data required are current and watts input at no-load, the current and watts input with the rotor blocked, and the resistance of the stator windings.

The induction motor diagram is similar in principle to that of a transformer; but, in the motor diagram, the diameter of the current locus is relatively much shorter on account of the greater magnetic leakage caused by the air-space. The air-gap of an induction motor introduces considerable reluctance into the magnetic circuit, the magnetising current, as compared to the load current, is relatively large at small percentages of the rated load.

The above description refers to the locus of the primary and secondary currents of a polyphase induction motor.

Example 14. A 20- B. H P., 440-volt, 50-cycle, 3-phase, 4-pole induction motor was tested and the following data were obtained. Line current =7·5 amperes. Power absorbed=1,200 watts. On short-circuit test: current =21 amperes.

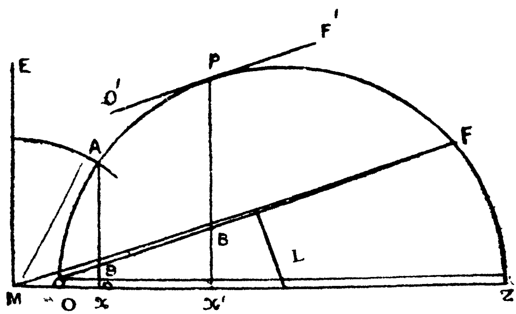


Fig. 3·41

Terminal volts=120. Power absorbed=1,400.

Solution :—

Power factor on no-load $= \dfrac{1{,}200}{1{\cdot}73 \times 440 \times 7{\cdot}5} = 0{\cdot}21.$

$\therefore$ the angle of lag (of which 0·21 is the cosine) of currents behind voltage $= 78^\circ$ Short-circuit current at 440 volts $= 0{\cdot}21 \times 440/120 = 77$ amperes.

Power factor on short circuit

$= 1{,}400/1{\cdot}73 \times 120 \times 21 = 0{\cdot}32.$

$\therefore$ the angle of lag of current behind voltage $= 71^\circ$.

Draw ME vertically from the left-hand end M of a base line MZ. ME represents the voltage vector. Next draw MO at an angle of 78° with ME and of such a length that it represents the no-load current to a scale of, say, 1 in. = 5 amperes. Also draw MF at an angle 71° with ME to represent to the same scale the short-circuit current of 77 amperes.

Then construct the semicircle APF.

I. To find the power factor at full-load :

Assume the full-load efficiency to be 86 per cent. and the full-load power factor to be 0·88 (see Table).

Full-load current

$= \text{B.H.P.} \times 746/1{\cdot}73 \times \text{line volts} \times \eta \times \text{p.f.}$

$= 20 \times 746/1{\cdot}73 \times 440 \times 0{\cdot}86 \times 0{\cdot}88$

$= 25{\cdot}9$ amperes.

With centre L and radius representing to scale (1 in. = 32 amps.) 25·9 amperes describe an arc cutting the semicircle at A. Join M and measure the angle EMA.

Full-load power factor $= \cos EMA$.

II. To find the full-load efficiency η :

Draw $ABCX$ parallel to EM cutting OF at B

Percentage efficiency $= (AB/AX) \times 100 = (17{\cdot}5/21) \times 100 = 83{\cdot}3$ per cent.

Note that the scale is immaterial, provided that both are measured in the same scale, in the efficiency. Now see if the assumed values of p f and η agree with what is obtained from the circle diagram. If they do not agree, substitute the calculated value of p.f. and η. This set may agree more closely ; if not, repeat the operation.

Table of Efficiencies and Power Factor for Three-Phase Induction Motor

B.H P.	Percentage Efficiency. η	POWER FACTOR			
		2-pole	4-pole	6-pole	8-pole
1	80				
5	85	0·87	0·82	0·71	0·70
10	86	0·89	0·85	0·81	0·77
20	88	0·91	0·88	0·85	0·82
50	89	0·92	0·90	0·88	0·86
100	90	0·93	0·92	0·91	0·89
150	91				
200	92				
300	93				

III. To find the maximum output and the overload capacity :

(*a*) Find the maximum distance between the arc OAF and the line OF. The simplest method is : draw $O'F'$ parallel to OF by means of set squares so that $O'F'$ just touches the arc. Suppose the point of contact is P.

(*b*) Draw PX_1 parallel to EM cutting OF at B'. Now PB' is the maximum distance along a perpendicular to MZ between the arc $OAPF$ and the line OF, *i.e.*, PB' represents the maximum output of the motor. Overload capacity = maximum output/full-load output.

$$= PB'/AB = 25/17\cdot5 = 1\cdot42.$$

$\therefore$ the maximum B. H. P $=1{\cdot}42\times20=28{\cdot}4$

143. Prof of the Circle Diagram —

Let—

$E_2 =$ the electromotive force induced in the rotor circuit at zero speed,

$R_2 =$ the resistance of the rotor circuit,

$X_2 =$ the reactance of the rotor circuit at zero speed,

$s =$ the slip of the rotor expressed as fraction of the synchronous speed,

$I_2 =$ the current in the rotor circuit at slip s,

$\phi =$ the phase angle between E_2 and I_2.

Then

$$I_2 = \frac{sE_2}{\sqrt{R_2^2 + s^2 X_2^2}} \qquad (a)$$

But $$sX_2/R_2 = tan\ \phi \qquad (b)$$

and $$R_2 = sX_2/tan\ \phi \qquad (c)$$

$$= sX_2\ cot\ \phi \qquad (d)$$

Substituting the value of R from equation (d) in equation (a),

$$I_2 = \frac{s\ E_2}{\sqrt{s^2 X_2^2 + s^2 X_2^2\ cot^2 \phi}} \qquad (e)$$

$$= \frac{s\ E_2}{sX_2 \sqrt{(1 + cot^2 \phi)}} \qquad (f)$$

$$= E_2\ sin\ \phi / X_2 \qquad (g)$$

Equation (g) is a polar equation of the circle.

*144. Analytical Equations and Deductions.

Let $n =$ synchronous speed of rotor in revolutions per minute,

$n' =$ the actual speed of rotor in revolutions per minute,

$T =$ secondary rotor torque at slip s,

$L_2 =$ the self-inductance of the secondary circuit due to leakage flux,

$E_2 =$ secondary E. M. F. at standstill,

$sE_2 =$ secondary E. M. F. at a slip s,

$I_2 =$ secondary current at a slip s,

* A. S. Mc Allister's Alternating Current Motors.

$X_2 =$ secondary reactance at standstill,
$sX_2 =$ secondary reactance at a slip s,
$R_2 =$ secondary resistance.

The reactance due to one phase of the secondary windings, when the armature is at a standstill and the slip equals unity, is

$$X_2 = 2\pi f L_2,$$

where L_2 is the self-inductance of the secondary winding due to leakage flux, and where s equals any fractional value other than unity, f=frequency of the current in the rotor at synchronous speed.

$sX_2 = 2\pi f_2 L_2$, but $f_2 = sf$, and at slip s $= 2\pi f L_2 s$.

Then $Z_2 = \sqrt{R_2^2 + s^2 X_2^2}$ = secondary impedance,

$$I_2 = \frac{sE_2}{\sqrt{R_2^2 + s^2 X_2^2}} = \frac{\sqrt{2}\,\pi A n_2 \phi f s}{10^8 Z_2} = \text{ secondary current,}$$

and

$$\cos\theta = \frac{R_2}{\sqrt{R_2^2 + S^2 X_2^2}} = \text{ secondary power factor.}$$

It will be seen that the power factor of the secondary circuit depends upon the slip, being approximately, near synchronism and decreasing with an increase of the slip. All the three expressions Z, I_2 and θ are taken at the slip s.

Torque is produced by the reaction of the secondary current upon the primary field. Thus the torque between the field magnet and armature is proportional to the integrated product of the rotating mutual magnetic flux with the secondary current.

The torque, which is zero at synchronous speed, rapidly rises to a maximum value with the increase of slip, and then falls to a comparatively low value at standstill. This decrease is due to the change in the

power factor in the secondary circuit and to a decrease of the primary field with the slip.

$$T=\frac{sE_2}{\sqrt{R_2^2+s^2X_2^2}}\times\frac{R_2}{\sqrt{R_2^2+s^2X_2^2}}\times K=\text{secondary torque}$$

at the slip s; where K is a constant depending upon the terms in which torque is expressed, and upon the magnetic field, the latter being here assumed constant.

In the wound rotor, the secondary resistance may be varied by means of the outside rheostat By continually keeping the total resistance in the secondary equal to sX_2, the same maximum torque may be obtained at all speed

Hence,

$T=R_2\ s\ E_2\ K/(R_2^2+s^2X_2^2)=$rotor torque at the slip s.

An examination of these formulæ reveals many of the characteristics of the induction motor, which is discussed at this point.

(1) The torque becomes maximum when $R_2=sX_2$.

(2) If R_2 be made equal to X_2, maximum torque will occur at standstill.

(3) Since at maximum torque $R_2=sX_2$, the torque is equal to $s^2X_2E_2\ K/2\ s^2X_2^2=E_2K/2X_2$, and the value of maximum torque is independent of the resistance.

(4) When X_2 is negligible, the torque$=sE_2\ K/R_2$, or the torque is directly proportional to the slip, near synchronism, and inversely to the resistance.

(5) At standstill the torque$=K\ R_2\ E_2/(R_2^2+X_2^2)$, which, when R_2 is less than X_2, can be increased by the insertion of resistance up to the point where the two are equal; further increase of resistance will then decrease the torque.

(6) The starting torque is proportional to the resistance and inversely proportional to the square of the impedance.

(7) Since power is proportional to the product of speed and torque, the output is equal to $P=A\ (1-s)\ KR_2\ sE_2/(R_2^2+s^2X_2^2)=A\ (1-s)\ T$, and is a maximum at

a slip less than that giving maximum torque, since it is the product of the speed and torque, and also A is a constant.

(8) $I_2 = \frac{sE_2}{\sqrt{R_2^2 + s^2 X_2^2}}$

and at maximum torque $R_2^2 = s^2 X_2^2$ Therefore, I_2 at maximum torque $= \frac{sE_2}{\sqrt{2}\, sX_2} = \frac{E_2}{\sqrt{2}\, X_2}$; whence it is plain that the secondary current giving maximum torque is independent of the secondary resistance.

(9) at maximum torque the secondary power factor $= 1/\sqrt{2} = 0{\cdot}707$.

(10) When the speed is near synchronism, as is the case under normal loads, the iron losses in the rotor are small due to the low frequency of the secondary current, and may be neglected The copper losses in the secondary are

$I_2^2 R_2 = s^2 E_2^2 R_2 / (R^2 + s^2 X_2^2) = sE_2\, T\, K$ and since E_2 is constant for constant impressed pressure, the copper loss of the secondary is proportional to the product of the slip and torque.

(11) For a given torque the slip is proportional to the copper loss of the secondary and independent of the secondary reactance or co-efficient of self-induction.

The copper losses in the secondary may also be expressed in terms of the voltage, current and power factor.

Copper losses in secondary $= sE_2\, I_2 \cos\theta$.

The electrical input into the secondary in terms of the secondary current, secondary voltage and power factor :

Input for rotor $= E_2\, I_2 \cos\theta_1$.

(12) The mechanical output P is equal to the electrical input *minus* the electrical losses in the secondary.

Mechanical output $P = E_2 I_2 \cos\theta - sE_2\, I_2 \cos\theta$
$= E_2\, I_2\, (1 - s) \cos\theta$.

$$P = \frac{sE_2}{\sqrt{R_2^2 + s^2 X_2^2}} \cdot E_2\, (1 - s) . \frac{R_2}{\sqrt{R_2^2 + s^2 X_2^2}}$$

$=R_2 sE_2^2 (1-s) / (R_2^2+s^2X_2^2)$ watts$=(T/K) E_2 (1-s)$
$=33{,}000\ sE_2^2\ R_2 (1-s) / \left\{ 746\times 2\pi n' (R_2^2+s^2X_2^2) \right\}$
$=33{,}000\ E_2^2\ sR_2 / \left\{ 746\times 2\pi n\ (R_2^2+ s^2X_2^2) \right\}$
$=7{\cdot}04\ sE_2^2\ R_2/n'\ (R_2^2 + s^2X_2^2)$ foot-pounds.

(13) If all losses except that of the secondary copper be neglected, the input will be

$$P+I^2R_2=(T/K)\ E_2\ (1-s)+TE_2\ s/K$$

and considering only the copper losses in the rotor and neglecting the primary losses in the secondary, a partial efficiency may be obtained from the above equation.

$$\text{Approximate efficiency} = \frac{\text{mechanical output}}{\text{rotor input}}$$

$$=E_2\ I_2\ (1-s)\cos\theta/E_2\ I_2\ \cos\theta$$

$$=\frac{(T/K)\ E_2\ (1-s)}{(T/K)\ E_2\ (1-s)+TE_2\ s\ K} = 1-s=n'/n;$$

which means that the approximate efficiency under the stated restriction is equal to the absolute speed in per cent. of synchronism. Since there must be losses in addition to that of the secondary copper, the efficiency is always less than the speed in per cent. of synchronism. However, to obtain the actual efficiency of the motor, all the losses must be taken into account, in addition to the copper losses. There are friction losses and iron losses in both the primary and the secondary. The expression in the equation above is of some interest, as it shows that the actual efficiency must always be less than the speed expressed in per cent. of synchronism.

(14) At a given slip the torque varies as the square of the primary pressure. This is seen from the fact that the secondary current at a given slip will vary directly as the strength of field, the power factor will remain constant, and, therefore, the torque, which is obtained from the product of secondary current power factor and field, will vary as the square of the field. Since the strength of the field varies directly with the primary pressure at a given slip, the torque will vary as the square of the primary pressure.

N.B.—The ratio n'/n ranges from 0·85 to 0·95 or more in commercial induction motors under full load, but the actual full-load efficiencies of induction motors range from 75 per cent. or even less for small motors to about 95 per cent. for very large motors.

145. Ratio of Rotor Voltages to Stator Voltages :—When the rotor and the stator are wound with the same number of conductors, when the rotor is standing still, the rotating magnetism induces in the rotor winding, E.M.Fs., of the same value and same frequency, as the electromotive forces induce in the stator winding, by the rotating stator magnetic leakage. Further, the E.M.Fs. induced in the stator winding are very nearly equal and opposite to the voltages applied to the stator winding, when the difference of the speeds of the rotor and stator magnetism is $(n-n')/n$ of the voltage applied to the stator winding; and the frequency of the E.M.F. induced in the rotor winding is a fractional part $(n-n'/n)$ of the frequency of the voltages applied to the stator winding. See diagrams showing the relationship of current, efficiency, torque, and speed, etc.

Example 15. The method of calculating the efficiency of the motor from the results of the test is best illustrated by a numerical example. It will be seen that the slip is required in order that the rotor I^2R loss may be separated from the total copper losses.

The results of no-load and full-load tests on a three-phase slip-ring motor were as follows: The intake, as measured by the two-wattmeter method, gave 1,080 and −660 watts on no-load, and 2,760 and 850 watts on full-load. The motor had four poles, the supply frequency was 50, full-load speed 1,460 R. P. M. Stator resistance between the terminals (R_t) 0·852 (hot) ohms. No-load current 7·8 amps., full-load current 13·7 amps. per line.

Solution :—

Stray losses + no-load stator I^2R loss

$$=1{,}080-660=420 \text{ watts.}$$

No-load stator I^2R loss

$$=(\sqrt{3}\,IL)^2 \times \frac{RC}{5}\left(\text{whether } \Delta \text{ or } Y\right)$$

$$=(\sqrt{3}\times 7\ 8)^2\times\frac{0.852}{2}$$

$=78$ watts (approx.).

$\therefore$ Stray losses $=420-78=342$ watts.

Full-load intake $=2{,}760+850=3{,}610$ watts full-load stator I^2R loss$=(\sqrt{3}\times 13.7)^2\times\frac{.852}{2}=240$ watts.

$\therefore$ Rotor intake $=3{,}610-(342+240)=3{,}028$ watts.

Synchronous speed $N_s=1{,}500$ R.P.M

Actual speed $N=1{,}460$ R.P.M.

$$\therefore\ \%\text{ slip } \frac{N_s-N}{N_s}\times 100=\frac{1{,}500-1{,}460}{1{,}500}\times 100$$
$$=2.66.$$

$$\therefore\quad \text{Rotor } I_2R \text{ losses}=\frac{2.66}{100}\times 3.028$$
$$=70 \text{ watts (approx).}$$

$\therefore$ Output $=$ rotor intake $-$ rotor I^2R loss
$=3{,}028-70=2{,}958$ watts

Intake $=3{,}610.$

$$\%\text{ efficiency}=\frac{2.958}{3{,}610}\times 100$$
$$=81.9\ \%.$$

Example 16. A motor at standstill takes 6 times full-load current with normal applied voltage, and develops 1.5 times full-load torque. What must the applied voltage be to obtain full-load torque and what will be the starting currents in the motor winding and in the line?

Solution :—

$$(E_2)^2/(E_1)^2=\frac{\text{full-load torque}}{1.5\text{ full-load torque}}=1/1.5$$

$$\therefore E_2=(\sqrt{1/1.5})\,E_1=0.815\,E_1,$$

or, 81.5 per cent. of normal voltage. The starting current in the motor

$$=6\text{ (full-load current) } E_2/E_1$$

$=4.89$ (full-load current)

$=I_m$.

Starting current in the line

$=4.89$ (full-load current) E_2/E_1

$=4.89$ (full-load current) 0.815

$=3.985$ (full-load current)

$=I_1$

Example 17. If a delta-connected motor at standstill takes 6 times full-load current with normal applied voltage and develops 1.5 times full-load torque, what is the starting current in the motor and also in the line, if the motor is Y-connected and what is the starting torque under these conditions ?

Solution :—

$$\text{The starting torque} = 1.5 \text{ (full-load)} \times (0.58)^2$$
$$= 0.5 \text{ (full-load torque)}$$

The starting current in the line when delta-connected $=I_s$, starting current in the motor when delta-connected $=I_s/\sqrt{3}$.

The starting current in the motor when Y-connected $=(I_s/\sqrt{3})\times 0.58=I_s/3$.

The starting current in the line when Y-connected $=I_s/3$. Now I_s is 6 times the full-load current; so that when the motor is Y-connected, the starting current in the line is $(1/3)\times 6$ or 2 times full-load current.

The starting torque is 0.5 times the full-load torque and if this is not sufficient to start the motor, then a starting compensator will be required. Fig. 3.44.

Example 18. A three-phase induction motor has a stator wound for 6 poles, and takes three-phase alternating currents at a frequency of 50 cycles, and a voltage of 220 between any two of the three supply mains. The rotor has the same number of conductors as the stator. The no-load speed of the rotor is 980 R.P.M. and its full-load speed is 940. The magnetic leakage is negligible. Find :—

(*a*) The synchronous speed ; (*b*) the electromotive forces (three-phase) induced in the rotor winding at no-load and at full-load ; (*c*) the frequency of the

electromotive forces induced in the rotor windings at no-load and at full-load.

Solution :—

(*a*) The synchronous speed, of the rotating magnetism in the stator, $n=120f/p=120\times50/6=1{,}000$ R. P. M.

(*b*) The electromotive forces (three-phase) induced in the rotor windings at no-lood are—

$(n-n'/n)\times$ voltage applied to stator

or $220\ (1{,}000-980)/1{,}000=4{\cdot}4$ volts.

The voltages induced in the rotor windings at full-load are $220\ (1{,}000-940)/100=13{\cdot}2$ volts.

It would be noted that if the slip of the rotor at no-load were zero, that is, if n' were equal to n, there would be zero electromotive force induced at no-load.

(*c*) The frequency of the E. M. Fs., induced in the rotor windings at no-load, is $(n-n')/n\times$ frequency of the stator voltage or $50\ (1{,}000-980)\ 1{,}000=1$ cycle per second.

The frequency of the E. M. Fs., induced in the rotor windings at full-load, is $50\ (1{,}000-940)/1{,}000=3$ cycles per second.

Example 19. A 220-volt, three-phase circuit feeds an induction motor. The current in each line wire is 150 amperes and the power taken by the motor is 50 kW. as indicated by the wattmeter. What is the power factor of the circuit ?

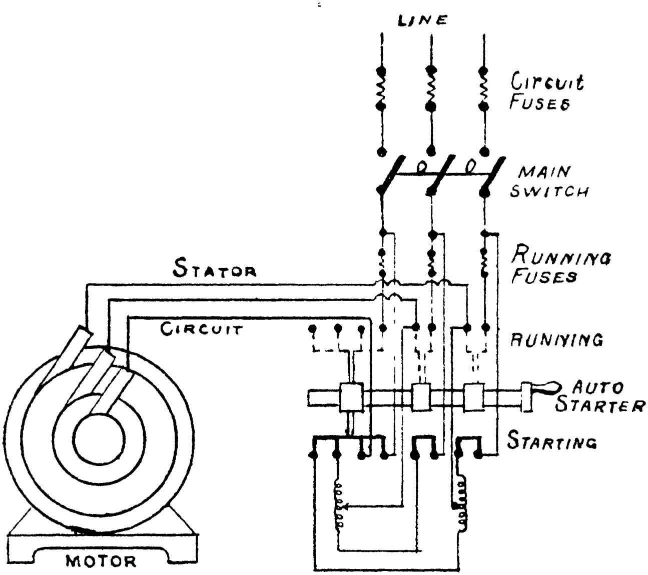
$$P=1{\cdot}73\ E_1\ I_1\ \cos\phi.$$

$$\therefore\ \cos\phi=0{\cdot}58\times50{,}000/150\times220$$

$$=0{\cdot}88.$$

146. Starting of Induction Motors.—

(a) Starting of Small Induction Motor.—By connecting directly to line, motors up to about 5 H. P. may be switched on to the line without any starting arrangement. A throw-over switch and two sets of fuses are all that are necessary to complete the equipment. Connect the motor to the line through the heavy fuses in the starting position, and the switch is thrown over, when



Starting Arrangement for Small Squirrel-Cage Three-Phase Induction Motor.

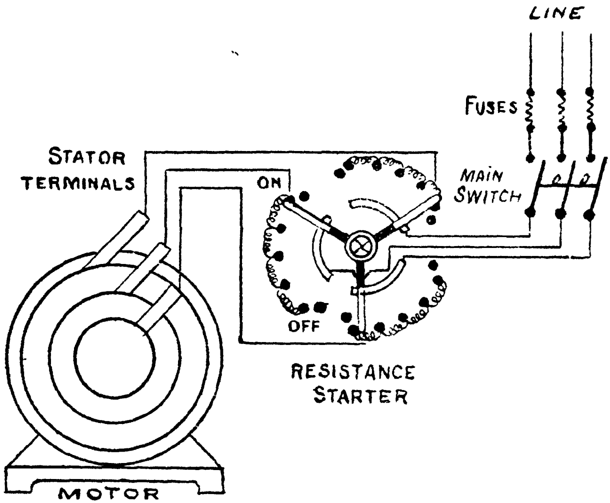
Fig. 3'42

the motor has run up to speed, inserting the fuses to protect the motor against heavy overloads.

(b) Starting Large Squirrel-Cage Motor.—By inserting external resistance to the line circuits, to reduce the heavy starting currents taken by the large squirrel-cage motor.

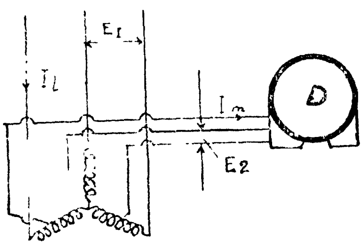
(1) **Resistance in the line circuit may be used.**—As the motor gets up speed, cut out the resistance in the stator. The resistance diminishes the voltage at the terminals, and, therefore, the torque of the motor. Hence, it can start only against light loads, the resistance is, however, quickly cut out when the motor can take 3 to

5 times its full-load currents. It is cheap in the first cost, and simple.



Starting Arrangement for Three-Phase Squirrel-Cage Induction Motor with Resistance Starter Inserted in the Stator or Line Circuit.

Fig. 3·43

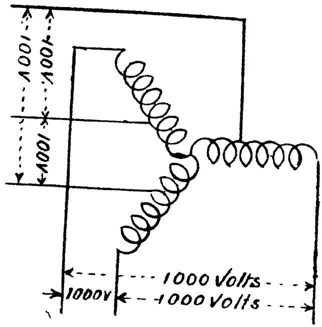


Starting Compensator for a Three-Phase Squirrel-Cage Induction Motor

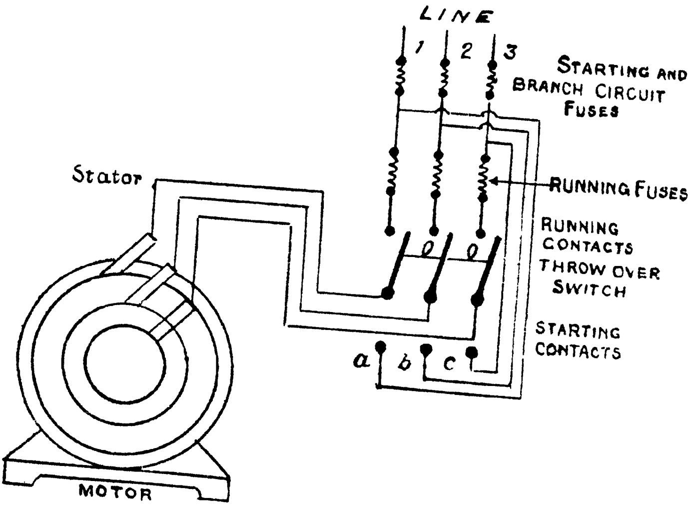
Fig. 3·44

(2) **An Auto-Transformer in the Circuit**—The voltage at the stator terminals is reduced by the transformer at the time of starting; but when the motor has been started, the auto-transformer is entirely disconnected by throwing over the switch to the running contact. As the auto-transformer reduces

the voltage at the motor terminals, it is impossible to start the motor under heavy load by this means. It takes less line current for the slow torque but is more costly and more complicated than the resistance method.



Connection of Three-Phase Auto-Transformer.
Fig. 3·45



Three-Phase Squirrel-Cage Induction Motor with Auto-Transformer Arrangement.
Fig. 3·46

To start, throw over the switch, put the motor in circuit with the line by means of the auto-transformer, and when the motor is got up speed, throw over the switch to the running terminals. Acted on by a spring the transformer is automatically cut out of the circuit.

(3) Star-Delta Method of Starting for Three-Phase Motor.—A change over switch connects up the stator windings in star, receiving only 0·58 of the line voltage when started, and then delta, receiving full-line volts when the motor has got up speed and when the switch is on the running position. This is very suitable for small motors not intended to run under heavy loads. It is not suitable for a motor which is required to exert an appreciable starting torque. It is only applicable to three-phase motors, whereas the auto-starter method may be used with either three or two-phase machines.

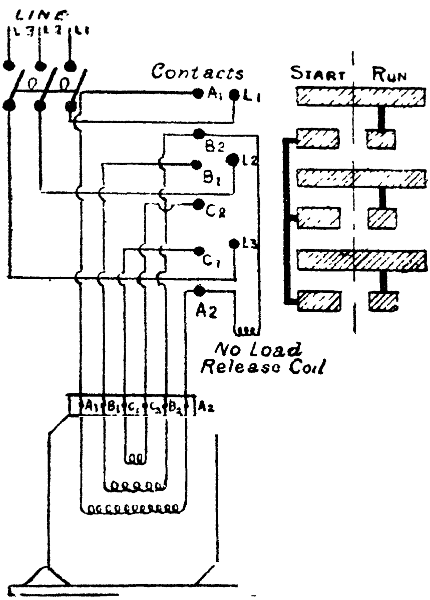
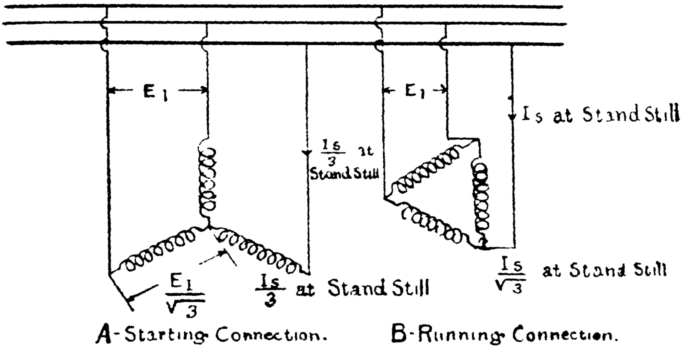


Fig. 3·47

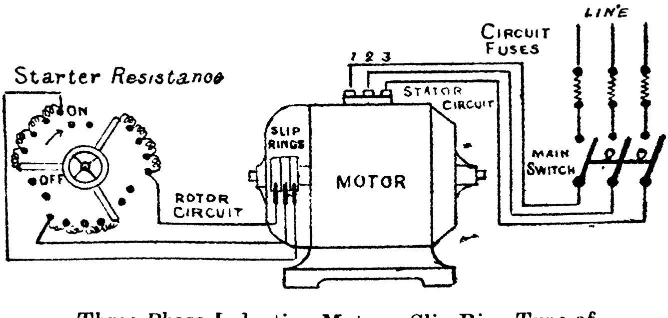
(4) Starting of Wound Rotor or Slip-Ring Motors.—By inserting internal resistance in the rotor circuit.



Star-Delta Starter for Three-Phase Induction Motor.

Fig. 3·48

The rotor circuit terminals of its windings are brought out to contacts or slip-rings, between which the resistances are inserted. The resistance is put in circuit at the start and the motor may be switched on directly to the line without danger ; the resistance is automatically cut out when the motor has attained full-speed.



Three-Phase Induction Motor ; Slip-Ring Type of Starter and Speed Regulator.

Fig. 3·49

147. To Reverse the Motor.—For a two-phase four-wire motor, interchange the connections of the two leads of either phase ; for a two-phase three-wire motor, interchange the two outside leads. For a three-phase motor, interchange the connections of any two motor leads.

Effect of Change in Voltage and Frequency on the Operation of Induction Motor :—These should be changed in the same direction. A variation of more than 10 °/o should not be tolerated Decreased voltage results in increased temperature rise and decreased speed and efficiency.

An induction motor operated on other than its rated frequency of supply, is capable of developing its rated torque if the voltage be altered in the same ratio as the frequency.

Example 20. A 230-volt, 50-cycle motor is rated at 15 H. P. and 840 R. P. M. ; what will be the speed and H. P. when the frequency is changed to 25 at one time and 60 at another time ?

Solution :—

The voltage at 25-cycle frequency

$$= 230 \times \frac{25}{50} = 115 \text{ volts.}$$

The speed will be $\frac{25}{50} \times 840 = 420$ R. P. M.

Th H. P. developed $= 15 \times \frac{420}{840} = 7\frac{1}{2}$

The voltage at 60-cycle $= 230 \times \frac{60}{50} = 276$ volts.

The speed will be $840 \times \frac{60}{50} = 1{,}008$ R. P. M.

The H. P. will be $= 15 \times \frac{60}{50} = 18.$

The most important effect of voltage variation is on the torque of the motor. Other factors being constant,

the torque of an induction motor varies with the square of the voltage applied to the primary windings. This factor is specially important when starting the motor and when operating it on overload.

Example 21. A motor is capable of carrying $2\frac{1}{2}$ times full-load torque when supplied at full voltage. What will be the torque developed by the motor if the voltage is reduced to 88 °/o of the rated value.

Solution :—

The torque developed will be $= (\cdot 88)^2 \times 2\frac{1}{2} = 1\cdot 9$ times the full-load torque.

This shows that the torque will be too small to carry the overload if the voltage is reduced 12 per cent. due to transformers, line conductors, etc. Thus the reduction of voltage and, due to it, the torque, have the important bearing on the starting characteristic of the induction motor ; and, where the induction motors are subjected to severe overloads, the transformers and supply cables should be of ample capacity to avoid the reduction of the load which the machine is capable of carrying without going out of steps.

148. Motor and Transmission Line.—When an induction motor is at the end of a transmission line on which constant voltage is impressed, the constant of the line should be added to those of the motor windings in determining the performance characteristics. Thus let Ro be the sum of the primary winding and the line resistances, and X_0 the sum of the primary windings and the line reactances. The performance curve should be drawn with these constants. Suppose that a 220-volt motor is at the end of a transmission line such that the maximum output occurs when the line drop has reduced the voltage on the motor to 200 volts, the maximum output is then $(200/220)^2 = 0\cdot 826$ its value under normal voltage.

If the performance curves at normal voltage are given, these may be changed to give approximately the performance under the conditions named by merely altering the scale of abscissæ.

149. Single-Phase Induction Motor.—This has essentially the same structure as the polyphase motor. The stator windings are, however, connected to a single-phase supply system. If one phase of a two-phase induction motor is opened while the motor is running, the machine will continue to rotate and carry the load, but a two-pole single-phase induction motor at standstill will not be self-starting because there the magnetic field produced by an alternating current is not rotating and there is no tendency for the rotor to turn. Its chief operating difference from the polyphase motor is that it is not inherently self-starting.

The chief difference between a single-phase and a polyphase induction motor lies in the magnetic field of the two machines. At synchronous speed each machine has got a true revolving field At standstill, the magnetic field of the polyphase motor revolves synchronously and is of more or less constant strength, the field of the single-phase machine is unidirectional in space and alternates in value.

(a) Shading Coil.—It is a closed winding placed around a portion of a pole. As the electromotive force of the supply circuit is reversed, the flux in the pole alternates, an E. M. F. is induced in the shading coil which opposes any change in the magnetic conditions existing in the space enclosed by the coil. This opposition causes the flux threading the coil to lag behind the flux in the unshaded part of the pole and thus to reach the maximum value at a later period. A flux which moves from the unshaded to the shaded part of the pole is thus produced and a small starting torque obtained. The stationary part consists of an electro-magnet with a laminated core, the winding of which is supplied with an alternating current. A disc of copper or aluminium passes

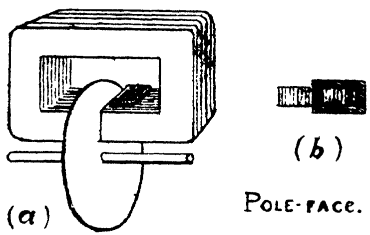
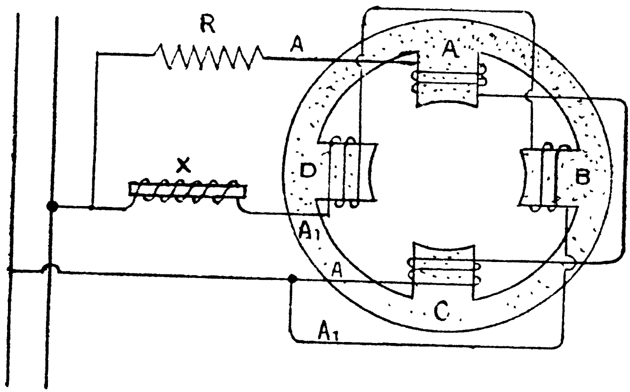


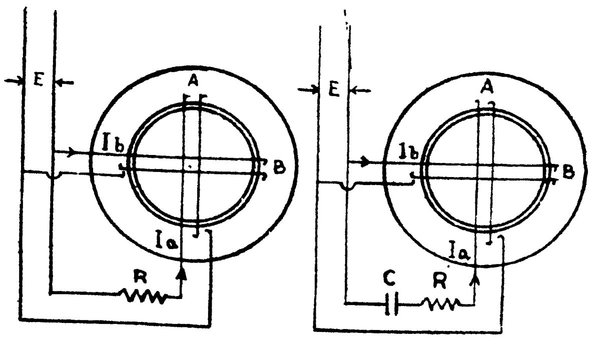
Fig. 3·50

through the narrow gap between the poles of the magnet. Electro-magnet shading coils are used in fans and small motors.

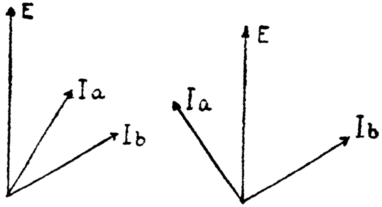
(b) **Split-Phase Winding.**—In this method an auxiliary stator winding must be provided and the motor is structurally a polyphase motor—Figs. 3·51-3·54.



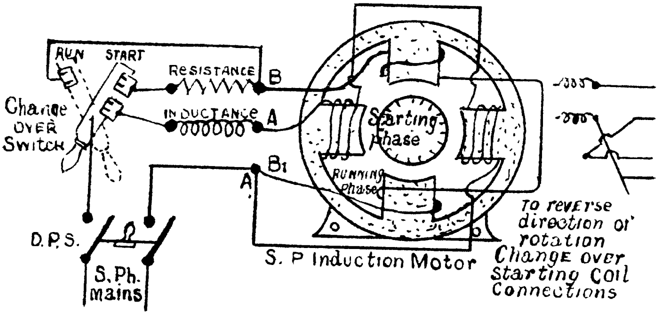
Split-Phase Arrangement.
Fig. 3·51



Connection Diagrams
Fig. 3·52



Vector Diagrams.
Fig. 3 53



Single-Phase Induction Motor with Split-Phase Winding for Starting.

Fig. 3·54

In this the stator has two distinct windings (Fig. 3·51), —one is on poles *A* and *C* and a non-inductive resistance is put in series with it, and the other on *B* and *D* with which is put in series an inductive resistance *X*, the circuits *AC* and *BD* are connected in parallel across the mains, the current in *AC* is in phase with the main current while that in *BD* lags behind the voltage. Hence, the supply current is divided into two currents having a large phase difference and thus resembling a two-phase supply. Thus the two windings produce a rotating magnetic field, as shown in the case of the polyphase induction motor, and the rotor is set in motion. Fig. 3·53 shows the vector diagrams.

When the rotor is in full-speed, the resistance R and reactance X and the starting winding BD are cut out and only the running winding AC is left in the circuits —Fig. 3'54.

*** 150. Complete Performance Diagram of the Single-Phase Induction Motor.**—The current diagram for the circuits is given in Fig. 3'55, where MN is the power and ON the wattless component of the primary current at synchronous no-load, while FW is the power and WM the wattless component of the primary current at standstill. The curve $OAFK$ is an arc of a circle having its centre on the line ON prolonged. OL is the "speed field" current (assumed constant in the diagram, but properly accounted for in the computations). LM is the "transformer field" current, while OM is the total primary current at synchronism.

The line FW drawn perpendicular to MW represents the total loss of the machine at standstill—the proper scale being used. MN indicates the so-called "constant" losses, while FZ shows the sum of the "added" primary and secondary copper losses. If the distance TZ be laid off to represent accurately the easily determinable "added" primary copper loss, then FY shows the "added" secondary copper loss. Straight lines being drawn to join

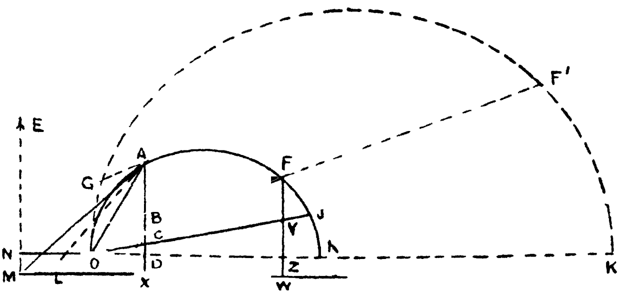


Fig. 3'55

*A. S. McAllister's Alternating Current Motors.

the point F and the point Y with O of Fig. 3·55, if from any point A on the circular arc $OAFK$ a perpendicular be dropped to the line MW, the following values may be taken at once from the diagram :—

OA is the "added" component of the primary current, OA is also the "added" component of the secondary current,—

AL is the total secondary current,
AM is the total primary current,
cos EMA is the power factor,
$MX \div AM$ is the power factor,
DX is the "constant" losses of the machine,
CD is the "added" primary copper loss,
CX is the total primary losses (including "speed field" excitation current loss in secondary),
BC is the "added" secondary copper loss,
BX is the total losses of the machine,
AX is the input to the machine,
BA is the output,
$BA \div AX$ is the efficiency,
AC is the total input to the secondary (excluding the "speed field" excitation current loss),
$(AB \div AC)^{\frac{1}{2}}$ is the speed with synchronism as unity,
$(AX \times AC)^{\frac{1}{2}}$ is the torque in synchronous watts.

151. The Frequency Changer or General Alternating Current Transformer.—(1) Alternating current plants for transmission of power use a low frequency, but lighting circuits require a high frequency ; hence, it is necessary, for such purpose, to raise the frequency of the circuit.

The frequency of the current in the rotor circuit is proportional to the slip. Thus a slip-ring rotor is driven at the proper speed, when a current of any desired frequency may be obtained from the rotor windings.

Hence, a frequency changer is essentially an induction motor, the rotor of which is driven mechanically by an auxiliary synchronous or induction motor supplied from the same system as in the stator of the frequency changer in a direction usually opposite to its natural

rotation. If the driving machine is synchronous motor, its fields may be overexcited to compensate for the lagging current of the frequency changer and the power factor of the supply circuit kept at a high value.

The current of lower frequency is led to the stator windings and the current of higher frequency is taken out of the rotor windings by means of collector rings.

(2) The frequency of the rotor current will depend on the speed at which the rotor is driven.

The total power delivered to a frequency changer is partly electrical power delivered directly from the low frequency supply mains to the stator of the frequency changer and partly mechanical power delivered by the belt to the rotor of the frequency changer from the auxiliary driving motor. The power output of the frequency changer is wholly electrical and in the form of suitable frequency alternating currents from the rotor.

(3) As there is no definite relation between the number of phases supplied to the stator and the number for which the rotor may be wound, the induction machine may be used to change the number of phases as well as the frequency of the system.

The chief objections to the use of induction motor as frequency or phase changer are its (1) poor regulation, (2) low power factor due to the large air-gap leakage reactance.

The frequency changer can be designed to change the electromotive force by using a suitable number of turns in the stators and rotor windings.

The electrical power delivered to the stator of the frequency changer is $f\,P/f'$ and the mechanical power delivered by the belt to the rotor of the frequency changer—

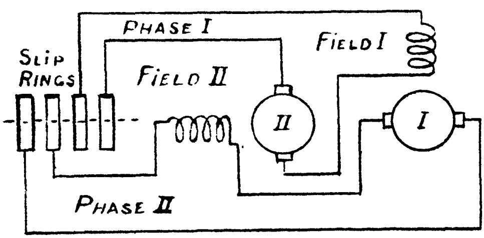
$$=P_m-(f'-f/f')\ P$$

where P is the total power delivered to the machine being a little greater than the total power delivered by

the machine at the increased frequency; f is the low frequency of the alternating current and supplied to the stator of the machine, and f' is the higher frequency of the alternating currents delivered by the rotor of the machine. The rotor is thus designed for the total output of power at the higher frequency and the stator for the intake of the power P.

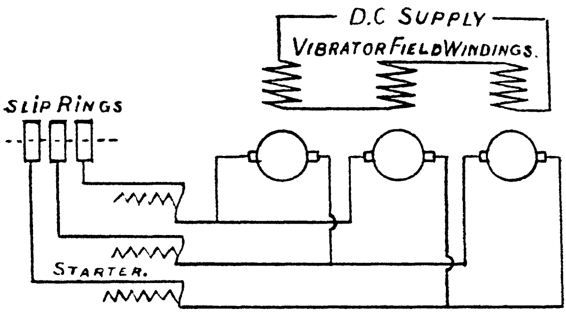
152. Phase Advancers.—The rotor of induction motors carrying current at a very low frequency corresponding to the slip, may be fitted with machines for excitation by means of low frequency currents supplied to the rotor windings. Such machines are called EXCITERS or PHASE ADVANCERS. The improvement in the power factor specially at light loads is effected by increasing the slip at full load. This increases also the overload capacity of the motors. Such a method is naturally only suited to the case of slip-ring motors and cannot conveniently be applied to the squirrel-cage type.

(a) **Slip-Ring Phase Advancer.**—*The Rotary Type.*—It is mechanically driven. This need not be excited by D.C. Each phase of the rotor winding forms a closed circuit with the corresponding exciter. It may be excited by A. C. in the stator coils or the flux may be due to currents in the rotor supplied through a commutator. Its magnetic axes are thus fixed. The higher the speed the greater the added E.M.F.



Leblance Two-Phase Exciter.

Fig. 3·56



Connection Diagram for Kapp Vibrator.
Fig 3·57

(b) The oscillatory type phase advancer consists of three armatures of the D.C. type for each phase connected in series with the rotor winding by means of slip-rings of the rotor but are free to move. Each element consists of a suitably excited two-pole field magnet carrying an ordinary continuous current armature which is connected to the rotor of an induction motor Such a vibrator is required in each phase. The rotor currents are sent through the armatures which oscillate at slip frequency from 1 to 3-cycles per second. This is due to the fact that a conductor carrying an alternating current in a continuous current field tends to move and in so doing, a leading E.M.F. is induced in it causing a leading current to flow which supplies the magnetising current of the motor, so that the latter will work at unit power factor with widely varying load The vibrator is put in circuit at starting and the starting resistance is cut out in the usual manner, there are no switches in the connection to the armatures of the vibrator. The E.M.F. of the vibrator leads the current; and so tends to advance the phase; and thus it acts like a condenser of large capacity. The E.M.F. varies (rotor current)/(slip frequency) and thus the angle, by which the current is advanced, increases as the load diminishes.

Advantages of Phase Advancer.—(1) A motor designed for use with an advancer can be rated higher and built more cheaply. (2) It considerably increases the overload capacity. (3) The over-all full-load efficiency is very slightly reduced, say, 0·5 per cent. (4) Slip is increased by using phase advancer.

153. Single-Phase Series Commutator Motor.—This is nothing but an ordinary D C. series motor(Fig. 3·58) except that it is generally provided with a series compensating winding distributed along the outer air-gap periphery. For, if we send an alternating current through a D. C. series motor, the field and armature currents reverse simultaneously so that an unidirectional torque is produced and the armature rotates. Another distinguishing feature of the single-phase motor is, that all the iron of the armature and field has to be completely laminated to avoid loss due to heating by eddy currents. For such a motor there will be two induced E M.Fs. induced in the armature. First, due to the rotation of the current carrying conductors in the magnetic field, there will be a dynamically induced E.M.F , and secondly due to the alternations in the flux, there will be a statically induced E.M.F. Hence, the motor shows a much greater tendency to sparks, and the two main problems met with in motors of this type are—

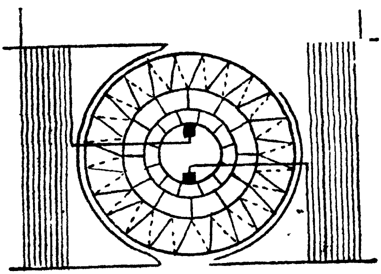


Fig. 3·58

(1) elimination of sparking,

(2) improving the power factor.

The armature can be compensated by employing coils carrying the armature current, and placed in such a way as to neutralise the armature flux, as shown in the figures.

In Fig. 3·59A, since the field flux is along *AB* and armature flux at right angles to it, the compensating winding must produce a flux along the axis *CD*.

These two can be replaced by a single field, as shown in Fig. 3'59B, since both of them are at right angles to one another. Another method of connection is as shown in Fig. 3'59 C, short-circuiting the compensating coil instead of connecting it in series with the main field. It then acts like the short-circuited secondary of a transformer, the primary being the armature winding. This method gives good compensation, since the fluxes of the primary and secondary neutralise one another.

Power Factor.—As we have already seen, one of the main drawbacks of a commutator motor is, that its power factor is too low. This can be improved by making the field coils of a few turns only to lessen the self-inductance

Commutation.—The other drawback of the A. C. motor is difficulty in obtaining sparkless commutation. Since at any instant there will be either the statically or dynamically induced E.M.F., it is difficult to obtain sparkless commutation. This is improved by—

(1) reducing flux density of the magnetic circuit,

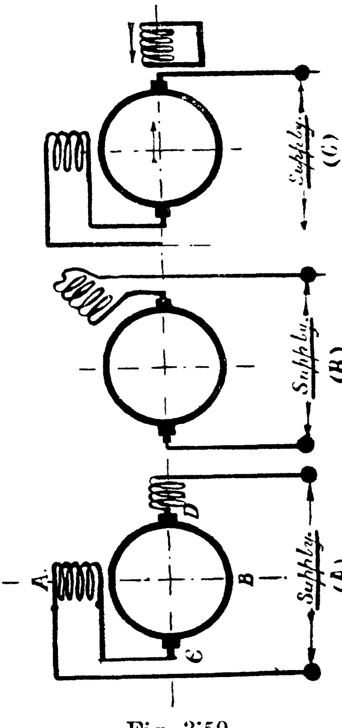


Fig 3'59

(2) reducing the number of series turns per armature coil,

(3) reducing the frequency of the supply,

(4) in addition to the above, employing the special devices mentioned below.

Special Devices.—These are mainly two: (1) high resistance leads. If, in spite of compensation, there is great difficulty in preventing sparking, it is usual to increase the resistance of the path taken by the current in the winding, as it is short-circuited at the brushes. This is done, as shown in the figure 3·59, by using high resistance leads between winding and commutator segments.

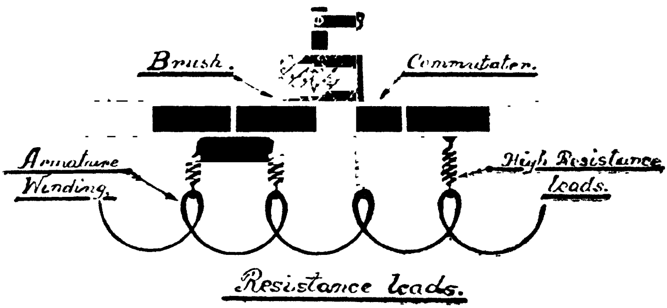


Fig. 3·60

(2) In this method we use balanced choke coils.

To avoid high armature reaction and to improve the power factor, compensating winding is usually employed. The inductance of the armature conductor may be neutralised by means of a compensating winding which is supplied with current (1) inductively, which is done by closing the winding on itself, or (2) conductively by connecting it in series with the armature winding. By properly proportioning the compensating winding and connecting it, so that its negative effect is opposite to that of the armature winding, the magnetic fields of the two windings neutralise each other.

The Compensating Winding.—This is a distributed winding imbedded in slots in the pole faces; and connected usually in series with the main field winding and the armature in such a manner that it sets up a magnetomotive force, which practically neutralises the effect of armature ampere turns.

Disadvantages.—(1) Large no-load current and low power factor, and the considerable air-gap necessary to reduce armature reactions.

(2) Increased iron losses.

(3) Sparking likely to take place at starting and with over-loads.

Advantages.—Great starting torque, convenient speed control.

154. Double Squirrel-Cage Induction Motors.—There are squirrel-cage motors having double winding on the stator. These are also called current displacement motors or Bouchrot motors (the name of the inventor). Often two separate windings are actually employed. But, sometimes, the windings consist of single bars resembling a double bell in cross-section. In the latter case, the outer portion of the conductor, near the periphery of the rotor, is of small cross-section than the inner portion, and is connected to the latter by a thin web of metal, the complete bar being of aluminium, cast into the deep and special-shaped slots. The basic principle is the use of one squirrel-cage winding of relatively high ohmic resistance near the surface of the rotor, and another of low ohmic resistance imbedded deep in the slots and, therefore, offering considerable inductive resistance. At the moment of starting, the frequency of the current induced in the rotor bars equals the supply frequency and, owing to the high inductance of the imbedded bars, most of the current flows in the outer bars, as these are of high ohmic resistance as a relatively high starting torque is developed, and the starting current is lower than that of a plane squirrel-cage machine. As the machine accelerates, the frequency of the current in the rotor winding decreases, and the current-flow is gradually transferred to the inner bars of low ohmic resistance.

155. Dual Frequency Induction Motors.—These are the motors designed to run on either of the two frequencies. The pole arrangement is such that the machine will run at the same speed on either of the two different frequencies. These are used at places where the power is supplied at non-standard frequency, and which will be

changed to standard frequency after a long period. The special arrangement of windings required involves extra initial expenses, and the product of efficiency and power factor may be about 5 % lower than for a single frequency motor. As a sacrifice of efficiency and power factor it is usually best to employ standard single frequency motors designed respectively for the existing and standard frequencies. Where such changes are expected, the first motor should not be purchased until it has been ascertained to get a standard frequency motor of the same output and dimensions.

156. Repulsion Motor.—In this the armature is not connected in series with the main circuit, but is short-circuited, and receives its current by induction.

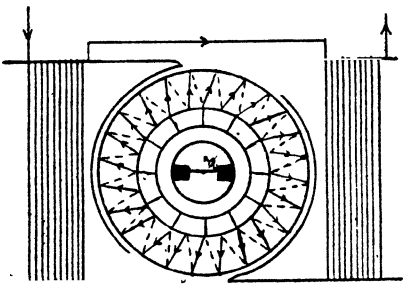


Fig 3 61

The field winding acts as the primary and the armature winding as the secondary of a transformer, and current flows between the short-circuited brushes. The function of the brushes is to short-circuit each coil (or group of coils) in turn as it (or they) reaches the best position for any position of the brushes, except, as shown in Fig. 3·61, where the algebraic sum of the voltages induced in the coil between the brushes is zero. In Fig. 3·62 the maximum current flows between the brushes. This current tends to set up a flux diametrically opposed to that set up by the field windings and the magnetic effect of the field winding is largely neutralised. The torque produced by the reaction between any current carrying conductor and the field flux is neutralised by an equal and opposite torque produced by some other armature conductor and the same field flux. The armature has, therefore, no tendency to rotate.

This equality of opposite torques is destroyed and the armature caused to rotate, by moving the brushes in either direction, the direction of rotation being the same as the movement of the brushes. The starting torque can be varied by slightly rotating

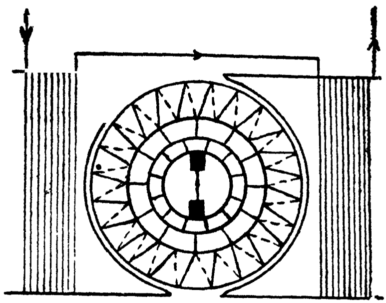


Fig. 3·62

* 157. Circle Diagram for Repulsion Motor.

—If the resistances of the windings and all other losses and magnetic leakage are neglected, the following relations hold between the quantities in a repulsion motor.

Let V_T be the voltage across the transformer winding T (Fig. 3·63); V_F the voltage across the field winding; ϕ_T=flux along axis of T, *i.e.*, BB; ϕ_F=flux perpendicular to BB.

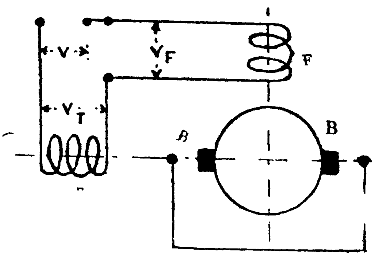


Fig. 3·63

Under the assumed conditions the E. M. F. produced by the transformer action of T in the armature circuit closed by BB must be equal to the back E. M. F. produced by the rotation of the armature in the field due to F.

∴ each of these E. M. Fs. is proportional to (ϕ_F × speed)

But the transformer E. M. F. $= V_T$ × ratio of turns in armature and in T; and V_T is proportional to ϕ_T.

∴ ϕ_T is proportional to (ϕ_F × speed).

* W. T. Maccall's Alternating Current Electrical Engineering.

At synchronous speed the inducing effects of rotation in a field and of the alternation of an equally strong field are equal. Therefore, at this speed $\phi_T = \phi_F$, in order to make the E. M. Fs. equal. Therefore, at any speed $\phi_T = S \times \phi_F$, where S is speed expressed as a fraction of synchronous speed.

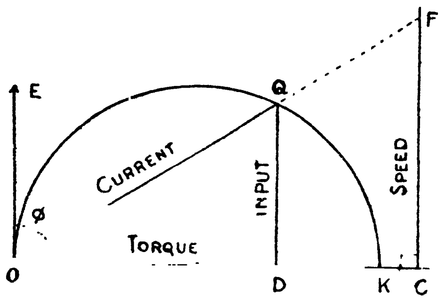


Fig. 3 64

$\therefore\ V_T / V_F = S \times r,$

where $r =$ ratio of (No. of turns in T) to (No. of turns in F). When a single-stator winding is used $r = cot$ (electrical angle of displacement of brushes).

Again, V_T is in phase with the current, and may be put equal to $I_1 R_L$, where $I_1 =$ motor stator current, and $R_L =$ a resistance equivalent to the load. Whereas, V_F leads the current by 90°, and equals $I_1 X$, where $X =$ resistance of field winding F.

Thus the current I_1 is that sent by a constant P. D., V, through a constant reactance, X, and a variable resistance, R_L. Therefore, the end of the current vector lies on a semicircle whose diameter is OK (Fig. 3·64), equal to V/X, and at right angles to the P. D. vector, OE. The proof is the same as for the rotor current of an induction motor. The speed is proportional to V_T/V_F, *i.e.*, to R_L/X, which is equal to $cot\ \phi$. It can, therefore, be represented in the same way as for the series-wound motor. An alternative method, applicable to the series-wound motor, too, is shown in Fig. 3·64. A line, CF, is drawn in any convenient position perpendicular to OK. The current vector is produced to cut this line in F. Then CF represents the speed to some scale.

For $CF = OC \cot CFO = \text{constant} \times \cot \phi$.

In the case of the repulsion motor, however, the speed scale can be found more easily than for a series-wound motor. For,

$\cot \phi = R_L/X = V_T/V_F = S \times r$.

Therefore, at synchronous speed $\cot \phi = r$, and so $CF = r.\ OC$, which determines the speed scale. The same relation determines the speed scale if the other method is used for representing speed.

The torque is represented by OD, as in the case of series-wound motor. But, since the speed scale can be found, the torque scale follows from this in a repulsion motor.

*** 158. Circle Diagram for Series-Wound Motor.**—The construction of the diagram may be proceeded with as follows :—Let OF be the standstill current plotted at its proper angle of lag behind the P. D. vector OE (Fig. 3·65). Calculate OS^2 × resistance of motor windings. *i.e.*, copper losses at standstill in watts. Draw FZ, equal to this on the input scale, parallel to EO. Draw ZO' perpendicular to EO. Describe a circular arc with centre on ZO' and passing through F and O ; and let this meet $O'Z$ produced in K. Join $O'F$. Carry out construction for speed, as described above

For any current represented by OP draw PD parallel to EO, and OD perpendicular EO. Let PD cut $O'F$ in O, and $O'K$ in N.

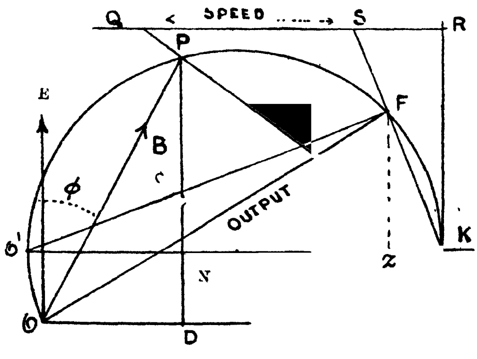


Fig. 3·65

* W. T. Maccall.

Then $\angle EOP = \phi$;

$$\left.\begin{array}{l} PD = \text{input}, \\ PC = \text{output} \\ \\ QS = \text{speed} \end{array}\right\} \therefore PC/QT = \text{torque (to some scale)}$$

The method of determining the scales is similar to that used for the induction motor. The scale for speed cannot be found in this way. Either the speed at one particular current or load must be known, or else one such speed must be calculated from the magnetic circuit and other constants of the motor.

This circle diagram is not as accurate as that of the induction motor, but it is useful for showing the approximate performance of an A. C. series-wound motor. It should not be used for determining the efficiency.

Advantage.—The field and compensating coil may be wound for high voltage, while the armature, wound for whatever voltage, must be suitable for the design in hand. The good starting torque offers means by which the single-phase induction motor is made self-starting, when the speed reaches a predetermined value. A centrifugal device removes the brushes from the commutator and short-circuits the commutator bars so that the armature conductors form a squirrel-cage motor.

159. The Compensated Repulsion Motor.—It is a series motor with short-circuited brushes placed in quadrature with the main brushes. It has shunt characteristics

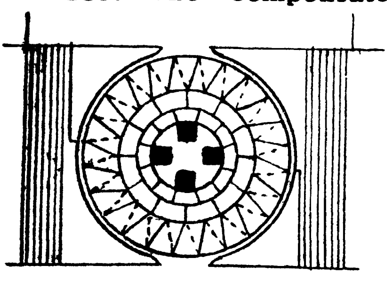


Fig. 3·66

The short-circuited brushes cause the armature winding to produce a magnetic field which opposes and largely neutralises the flux set up by the field winding. The current, which flows between the short-circuited brushes, is produced by transformer action.

The current flowing between the main (series) brushes sets up a field at right angles to the line joining the short-circuited brushes. This flux, reacting with the current flowing in the armature conductor, by reason of the short-circuited brush connection, produces the greater part of the torque of the motor, although some torque is doubtless produced by a reaction between the series field flux and the current between the main series brushes.

As the armature speed increases, the counter electromotive force, induced in the conductors by reason of their motions, reduces the current flowing between the short-circuited brushes, and the torque becomes less. Therefore, the flux is approximately constant, the current varies inversely with the speed of the armature and the motor has shunt characteristics.

160. Concatenation Control.—A common defect in the usual methods of speed regulation is the low efficiency at speeds far below synchronism. In order, therefore, to run at high efficiency at reduced speed some method of decreasing the synchronous speed must be adopted.

The synchronous speed of a motor is equal to the alternations of the system divided by the number of poles of the motor. If, therefore, a motor is arranged for two different numbers of poles, it will have two different synchronous speeds.

With mechanical connection between two motors, "concatenation" or "tandem" control also offers a means of reducing the synchronous speed. In practice, the secondary of one motor is connected to the primary of the other, the primary of the first being connected to the line. The frequency of the current in the secondary of any motor depends upon its slip. At standstill, therefore, the frequency impressed upon the primary of the second motor will be that of the line. As the motor increases in speed, the frequency of the secondary of the first motor decreases, and at half speed the frequency impressed upon the primary of the second motor will be equal to the speed of its secondary; that is, it will have reached its synchronous speed. If, now, the primary of the second motor be

connected to the supply circuit and the secondary of the first motor be connected to a resistance, the motors will tend to increase in speed up to the full synchronism of the supply.

By the use of suitable selected resistances for the secondary circuits of the two motors, this method gives the results as the series-parallel control of direct-current series motors, with one important distinction, however. The series-wound motors tend to increase indefinitely in speed as the torque is diminished, while the induction motors tend to reach a certain definite speed, above which they act as generators. In this respect they resemble quite closely to two shunt motors with constant field excitation, having armatures connected successively in series and in parallel, with and without resistance; and like the shunt motors, when driven above the normal speed, they feed power back to the supply.

161. To calculate the Current, Power Factor, Efficiency of any Single-Phase Alternating Current Motor, or Horse-Power Output, the following formulæ may be used—

Let I = current in either line wire in amperes.
P. F. = power factor expressed decimally.
η = efficiency of motor expressed decimally.
H. P. = horse-power output.
V = impressed voltage between wires at motor terminals in volts.

To calculate—

I. Current.
I = H. P. × 746/V × P. F. × η

II. Power factor.
P. F. = H. P. × 746/V × I × η

III. Efficiency.
η = H. P. × 746/P. F. × V × I

IV. Horse-power.
H. P. = V × I × P. F. × η/746

Example 22. If the rated H. P. of a motor were 20, the voltage of supply 220, and the motor was guaranteed

an efficiency of 85 per cent. at this output, and a power factor 80 per cent., what current would the motor take, and what size fuses would you insert in its starting circuit, allowing five times the normal full-load current value ?

Solution :—

Substituting the values given in Eq. I.—

$I = 20 \times 746/220 \times 0{\cdot}80 \times 0{\cdot}85 = 99{\cdot}7$ amperes.

The fuse value would equal five times this $= 5 \times 99{\cdot}7 = 498{\cdot}5$ amperes.

Example 23. A certain single-phase motor on a 220-volt circuit takes 20 amperes, and a wattmeter placed in the circuit shows a reading of 3,520 true watts. Find the power factor of the motor.

Solution :—

Power factor = actual watts/apparent watts
= true input in watts/volt-amperes.

Thus :—P. F. = 3,520/220 × 20 = 176/220 = 0·8

162. To calculate the Current, Power Factor, Efficiency of any Two-Phase Alternating Current Motor, or Horse-Power Output.

Let I = line current in either phase in four-wire supply, current in either outer in three-wire supply, or 0·707 current in common wire.

P. F. = power factor expressed as a decimal.

η = efficiency expressed as a decimal.

H. P. = horse-power output.

V in four-wire supply = volts in either phase.

I. Current.
$I = \text{H. P.} \times 746/V \times \text{P. F.} \times \eta \times 2$

II. Power factor.
$\text{P. F.} = \text{H. P.} \times 746/V \times I \times \eta \times 2$

III. Efficiency.
$\eta = \text{H. P.} \times 746/V \times I \times \text{P. F.} \times 2$

IV. Horse-power.
$\text{H. P.} = V \times I \times \text{P. F.} \times \eta \times 2/746$

Example 24. What would be the power factor of a two-phase motor taking 25 amperes in each of its four-line supplies, and designed to run on 220-volt circuit. At this current its H. P. is rated at 10, and its efficiency 80 per cent.

Solution :—

Substituting these values in Eq. II.—

P. F. $=10\times 746/220\times 25\times 0{\cdot}80\times 2$

$=84$ per cent. or $0{\cdot}84$.

Example 25. A certain 220-volt two-phase motor, having an efficiency of 85 per cent. and a power factor of $0{\cdot}8$, develops 15 B. H. P. Find the current taken per phase—*i.e.*, in each of the two pairs of conductors.

Solution.—

1st step.—B. H. P. per phase $=15/2=7{\cdot}5$.

2nd step.—Find current per phase.

Here we use the formula :—

$I=$ B. H. P. $\times\ 746/V\times\eta\times$ P. F.

$=7{\cdot}5\times 746/220\times 0{\cdot}85\times 0{\cdot}8=37{\cdot}3$ amperes.

Thus each of the four wires has to carry, say, 37 amperes.

$\therefore$ Total B. H. P. of motor $=2\times$ B. H. P. per phase.

$=2\times 10=20.$

163. To calculate the Current, Power Factor, Efficiency of any Three-Phase Alternating Current Motor, either Mesh or Star-Connected, or Horse-Power Output.

Let H. P. = horse-power output.

$V=$ voltage between any two of the three-line wires of the balanced system.

$I=$ current in amperes in each of the three-line wires.

P. F. = power factor of motor expressed as a decimal.

$\eta=$ efficiency of motor expressed as a decimal.

I. Current.

$I=$ H. P. $\times\ 746/V\times$ P. F. $\times\ \eta\times 1{\cdot}73$

II. Power factor.

$$\text{P. F.} = \text{H. P.} \times 746/V \times I \times \eta \times 1{\cdot}73$$

III. Efficiency.

$$\eta = \text{H. P.} \times 746/V \times I \times \text{P. F.} \times 1{\cdot}73$$

IV. Horse-power.

$$\text{H. P.} = V \times I \times \text{P. F.} \times \eta \times 1{\cdot}73/746$$

Example 26. A two-phase 220-volt motor supplied from three-wire distribution mains, and having an efficiency of 88 per cent. and a power factor of 0·8, develops 25 B. H. P. Find the current per phase taken by the motor, the current in the middle wire, and the voltage across the two outer wires.

Solution :—

1st step.—B. H. P. per phase$=25/2=12{\cdot}5$.

2nd step.—Find current per phase.

We have by the formula :—

$$I = \text{B. H. P.} \times 746/V \times \eta \times \text{P. F.}$$

$$= 12{\cdot}5 \times 746/220 \times 0{\cdot}88 \times 0{\cdot}8 = 60{\cdot}2 \text{ amperes.}$$

3rd step.—Find the current in the middle wire.

By formula :—

$$\text{Current in middle wire} = 1{\cdot}414 \times \text{phase current}$$

$$= 1{\cdot}414 \times 60{\cdot}2$$

$$= 85 \text{ amperes.}$$

4th step.—Find voltage between the two outer conductors.

By formula :—

$$\text{Voltage across the outers} = \text{phase voltage} \times \sqrt{2}.$$

$$= 220 \times 1{\cdot}414.$$

$$= 311 \text{ volts.}$$

Example 27. A two-phase 220-volt motor, having an efficiency of 85 per cent. and a power factor of 88 per cent., takes a current of 50 amperes per phase. What is its B. H. P. ?

Solution :—

The B. H. P. per phase can be calculated thus :—

$$\text{B. H. P. per phase} = V \times I \times \eta \times \text{P. F.}/746$$

$$= 220 \times 50 \times 0{\cdot}85 \times 0{\cdot}88/746.$$

$$= 10{\cdot}02, \text{ say, } 10.$$

Example 28. What will be the efficiency of a 220-volt three-phase induction motor taking a full-load current of 50 amperes? Its P. F. at full load is stated to be 70 per cent. and its rated full load output 17 H. P.

Solution :—

Substituting these values in Eq. III.—

$$\eta = \frac{17 \times 746}{1{\cdot}73 \times 220 \times 50 \times 0{\cdot}70} = 0{\cdot}95 \text{ or } 95 \text{ per cent.}$$

Example 29. Calculate the current taken in each line by a certain three-phase motor, which is fed at 450 line volts and develops 100 B. H. P. At this load the motor in question has an efficiency of 90 per cent., and its power factor is 90.

Solution :—

The formula to be used here in transposition :—

$$I = \frac{\text{B. H. P.} \times 746}{V \times 1{\cdot}73 \times \eta \times \text{P. F.}}$$

$$= \frac{100 \times 746}{450 \times 0{\cdot}9 \times 1{\cdot}73 \times 0{\cdot}9}$$

$= 118$ amperes.

Example 30. Find the apparent input in K. V. A. of a 20-H. P. three-phase motor supplied at 220 line volts, if its efficiency is 87 per cent. and its power factor 91 per cent. at that load. Also find the full-load line current, and the phase current, assuming the machine to be mesh-connected.

Solution :—

1st step.—Find the apparent input in K. V. A. By using formula we have :—

$$\text{K. V. A.} = \frac{\text{B. H. P.} \times 746}{1{,}000 \times \eta \times \text{P. F.}}$$

Substituting the known values we get :—

$$\text{K. V. A.} = \frac{20 \times 746}{1{,}000 \times 0{\cdot}87 \times 0{\cdot}91} = \frac{14{,}920}{791{\cdot}7} = 18{\cdot}8$$

2nd step.—Find the full-load line current.

First, bring the K. V. A. to volt-amperes by multiplying by 1,000.

Thus :—

V. A. $=18{\cdot}8\times1{,}000=18{,}800$.

Then, find line current I by dividing the V. A. or apparent watts by the line voltage multiplied by $\sqrt{3}$. Thus :—

$$I=\frac{\text{volt-amperes}}{\sqrt{3}}$$

$$i.e.,\ I=\frac{18{,}800}{220\times1{\cdot}73}=4{\cdot}67 \text{ amperes.}$$

3rd step.—Find the full-load phase current.

It follows from the formula that :—

$$\text{Phase current}=\frac{\text{line-current}}{\sqrt{3}}$$

$$=\frac{46{\cdot}7}{1{\cdot}73}=26{\cdot}9 \text{ amperes.}$$

Example 31. A 450-volt three-phase motor takes a line current of 100 amperes, and develops 80 B. H. P., its efficiency being 90. Find its power factor.

Solution :—

By transposing the formula we get :—

$$\text{P. F.}=\frac{\text{B. H. P.}\times746}{V\times I\times\eta\times1{\cdot}73}$$

$$=\frac{80\times746}{450\times100\times0{\cdot}9\times1{\cdot}73}=0{\cdot}85 \text{ or } 85 \text{ per cent.}$$

Example 32. An induction motor and a synchronous motor, each rated at 2,200 volts, are to be run in parallel at the end of a transmission line having a resistance $R=0{\cdot}8$ ohm, and an inductive reactance $X_L=1$ ohm. The average power and current taken by each motor

when operated at rated voltage with the particular load it has to carry are :—

$$\text{Induction motor} \left\{ \begin{array}{l} V_i = 2{,}200 \text{ volts,} \\ I_i = 473 \text{ amperes,} \\ P_i = 746 \text{ kilowatts.} \end{array} \right.$$

$$\text{Synchronous motor} \left\{ \begin{array}{l} V_s = 2{,}200 \text{ volts.} \\ I_s = 236 \text{ amperes.} \\ P_s = 373 \text{ kilowatts.} \end{array} \right.$$

Find :—

(1) the resultant power factor of the load measured at the motors, (2) the voltage at the power station and of the line in order to maintain 2,200 volts at the motors when running under average load conditions, (3) the resultant power-factor measured at the station end of the line.

Solution :—

An induction motor always takes a lagging current. The excitation of the synchronous motor is adjusted so that it takes a leading current.

(1) The equivalent constants of the motor loads are :—

Induction motor :

$$Y_i = I_i / V_i = 473/2{,}200 = 0{\cdot}215 \text{ mho.}$$

$$g_i = P_i / V_i^2 = 746 \times 1{,}000/(2{,}200)^2 = 0{\cdot}154 \text{ mho.}$$

$$b_i = \sqrt{Y_i^2 - g_i^2} = \sqrt{(0{\cdot}215)^2 - (0{\cdot}154)^2} = 0{\cdot}15 \text{ mho.}$$

Synchronous motor :

$$Y_s = I_s / V_s = 236/2{,}200 = 0{\cdot}1073 \text{ mho.}$$

$$g_s = P_s / V_s^2 = 373 \times 1{,}000/(2{,}200)^2 = 0{\cdot}077 \text{ mho.}$$

$$b_s = \sqrt{Y_s^2 - g_s^2} = \sqrt{(0{\cdot}1073)^2 - (0{\cdot}077)^2}$$
$$= 0{\cdot}0742 \text{ mho.}$$

The equivalent susceptance b_s of the synchronous motor is negative since the synchronous motor takes a leading current.

$$g_o = g_i + g_s = 0{\cdot}154 + 0{\cdot}077 = 0{\cdot}231 \text{ mho.}$$

$$b_o = b_i + b_s = 0{\cdot}15 - 0{\cdot}0742 = 0{\cdot}0758 \text{ mho.}$$

$$R_o = g_o/(g_o^2 + b_o^2) = 0{\cdot}231/\{(0{\cdot}231)^2 + (0{\cdot}0758)^2\}$$
$$= 0{\cdot}231/0{\cdot}0591 = 3{\cdot}9 \text{ ohm.}$$
$$X_o = b_o/(g_o^2 + b_o^2) = 0{\cdot}0758/\{(0{\cdot}231)^2 + (0{\cdot}0758)^2\}$$
$$= 0{\cdot}0758/0{\cdot}0591 = 1{\cdot}283 \text{ ohm}$$
$$Y_o = \sqrt{g_o^2 + b_o^2} = \sqrt{(0{\cdot}231)^2 + (0{\cdot}0758)^2}$$
$$= \sqrt{0{\cdot}0591} = 0{\cdot}2431 \text{ mho.}$$

The resultant power factor of the load measured at the motors is

$$\cos\phi_o = g_o/Y_o = 0{\cdot}231/0{\cdot}2431 = 0{\cdot}95$$

(2) The current taken by the two motors in parallel is

$$I_o = V_o Y_o = 2{,}200 \times 0{\cdot}2431 = 534{\cdot}82 \text{ amperes.}$$

Also $\tan\phi_o = b_o/g_o = 0{\cdot}0758/0{\cdot}231 = 0{\cdot}328 = \tan 18^\circ\text{-}10'$

The current I_c, therefore, lags the voltage V_o impressed on the motors in parallel by 18°-$10'$.

The voltage V_o at the station, which will give 2,200 at the motor, is

$$V_o = I_o\sqrt{(R_o + R)^2 + (X_o + X_L)^2}$$
$$= 534{\cdot}82\sqrt{(3{\cdot}9 + 0{\cdot}8)^2 + (1{\cdot}283 + 1)^2}$$
$$= 534{\cdot}82\sqrt{(4{\cdot}7)^2 + (2{\cdot}283)^2}$$
$$= 534{\cdot}82 \times 5{\cdot}225$$
$$= 2{,}794 \text{ volts.}$$

(3) The power factor at the station is

$$\cos\phi_o = \frac{R_o + R}{\sqrt{(R_o + R)^2 + (X_o + X_L)^2}}$$
$$= 4{\cdot}7/5{\cdot}225 = 0{\cdot}9$$

The current lags the voltage at the station since $\tan\phi_o = (X_o + X_L)/(R_o + R_L)$ is positive.

164. Hunting of Induction Motors—An induction motor will rarely cause trouble by hunting. The phenomenon occurs as a speed variation of 1 or 2 per cent. on either side of the normal speed, with a corresponding period of vibration. This may be in any case from 10 to 500 swings per minute.

The hunting of induction motors depends upon the drop in the line between the generator operating the

motor and the motor itself, and upon the design and slot relation of field and armature. If the line resistance between the motor and the generator be cut off, the hunting will cease. This may not always be possible. In the case of a three-phase motor the trouble is sometimes stopped by changing from delta to Y-connection, or possibly by changing the grouping of the poles. In any case, the flux in the motor is altered.

The period of hunting has nothing whatever to do with the hunting of the generator. Hunting of a motor may occur even if the generator speed is exactly uniform. Such a case is quite distinct from a variation of the uniformity of the speed of the generator due to the engine driving, which lack of uniformity is repeated by the motor itself. This fault is more dangerous, as it usually results in a gradual increase of amplitude of swing until the motor gets swinging so badly that it finally breaks down and stops altogether. The manufacturer is sometimes responsible for this; but a change in the connections will often remedy the trouble and keep the machine in operation so long as a permanent correction is not effected.

165. The Factors to be Considered when Designing a Motor-Drive for a Machine are:— (1) the space available, (2) the surrounding conditions, (3) the nature of the load, (4) the speed of the shaft where power is to be applied, (5) the speed of the motor used, and the method of connecting the motor mechanically:—(*a*) direct connected, (*b*) belted, (*c*) geared, (*d*) connected by chain drive.

166. Speed Control of Polyphase Motors (*Vide* **Art. 132):**—The speed of polyphase motors can be controlled by a number of different methods, of which the followings are the most important: (I) Adjusting the resistance of the secondary circuit. This method is not suitable for service requiring several constant speeds with varying torque, such as machine tool work, but is very useful where constant speeds are not essential. The efficiency is reduced. (II) Adjusting the primary voltage. The voltage variation is obtained by adjustable resisters,

auto-transformers or choke coils in series with the primary. It has poor speed regulation, low efficiency and unsatisfactory control, specially when the primary voltage is high. Squirrel-cage motors are generally so started. (III) Using two motor primaries, one of which is capable of being rotated. (IV) Changing the number of motor poles. (V) Operating two or more motors connected in cascade. (VI) Adjusting the frequency of the primary current. (VII) Changing the number of phases of the secondary windings.

The results obtained by the use of these various methods differ widely, so that in selecting a variable speed alternating-current motor careful consideration must be given to the characteristics of the method of control, in order to determine its suitability for the service. In many cases a combination of methods is required in order to produce the desired speed changes.

COMPARISON OF D. C. and A. C. MOTORS

Direct Current.	Alternating Current.
1. Voltage limited to about 240 volts, if the same source is used for lighting.	1. The voltage can be easily transformed, using voltages suitable for lamps and motors.
2. Maintenance higher, owing to commutators.	2. Absence of commutators makes motor more rugged. It will stand larger momentary overloads; there is no danger of fire from sparks from commutator and it is more reliable.
3. Wide speed adjustment by simple means, with high efficiency.	3. Speed adjustment is difficult and motor is less efficient at reduced speeds.
4. Motors have better starting performance for cranes and elevators.	4. Operation is not satisfactory on high-speed elevators and large cranes. Starting current is greater.
5. Starting current is lower for usual types of constant speed motors.	5. Starting current for ordinary type is large. Special arrangements necessary to reduce it.
	6. A somewhat larger generator is required for a given motor load.

MOTORS FOR INDUSTRIAL PURPOSES

PERFORMANCE OF A. C. MOTORS

Type.	Starting Torque.	*Running Performance.	Applications.
1. Two or three-phase, squirrel-cage (low-slip).	Relatively low. Starting current high.	Speed nearly constant. About 3 to 6 °/o drop from no-load to full-load. Speed not adjustable.	Small blowers, cement and steel mills, screw machines, lathes, drills, pumps, conveyers, wood-working machinery.
2. Squirrel-cage (high-slip).	Higher than (1). Starting current less.	Speed decreases rapidly with load, somewhat like compound D. C. motor.	Small cranes and elevators, punches and shears, large band saws.
3. Slip-ring ...	Higher than (1) and (2). Starting current small.	With starting resistance out, acts like (1). With resistance in circuit, speed can be adjusted to any desired value at a sacrifice in efficiency.	Elevators, cranes, air-compressors, ventilating fans, steel mills, hoists, woodworking machinery.

Type.	Starting Torque.	*Running Performance.	Applications.
4. Single-phase (split-phase).	Low starting torque. Large starting current.	Similar to (1) ...	Used only in small sizes. Employed for constant speed applications only, such as small printing presses, sewing machine, etc.
5. Single-phase (repulsion).	Fairly high starting torque, but not as good as poly-phase motors.	Similar to (1) ...	For constant-speed applications. Used principally in sizes below 15 H. P. where only single-phase service is available.
6. Synchronous.	Low starting torque, large current.	Speed constant and cannot be adjusted.	Large air compressors, line shafts, pumps.

* Vide Performance Curves.

MACHINE TOOLS.	H. P.
Lathes—	
Screw-cutting up to 6-in. centres ...	½—1
Screw-cutting 12-in. to 30-in. centres ...	2—5
Engine 60-in. to 84-in. centres ...	5—10
Face 5-ft. face-plate ...	2—3
„ 10 ft. „ „	5—10
Turret	2—4
Drills—	
Portable	½—2
Small sensitive	¼—½
Vertical	½—4
Radial, 4 ft. to 6 ft.	2—4
Boring mills—	
3 ft. to 9 ft.	5—10
Vertical	2—4
Milling machines—	
Small	½—1
Medium universal	2—4
Milling Machines Heavy	5—15
Slotters, 12-in. to 24-in. stroke	5—10
Shapers, 18-in. to 30-in. stroke	2—4
Planers, 6 ft. × 2 ft. × 2 ft.	3—5
12 ft. × 5 ft × 5 ft.	10—15
24 ft. × 12 ft. × 12 ft. (double-head) ...	40
Punches, medium	2—6
Shears	7—15
Cold saws, 12-in. to 24-in.	2—5
Bending rolls	3—20
Riveting machines	3
Countersinking machines	3½
Grindstones	1½—3

* J. W. Meares' Electrical Engineering Practice.

MACHINE TOOLS.	H. P.
High-speed abrasive wheels—	
Up to 12-in. diameter	½—1
18-in. to 30-in. „	2—3
Forge fan, 24 fires	10

WOODWORKING MACHINERY.	H. P.
Saws—	
Circular 24-in. diameter	5—10
„ 48-in. „	25—35
„ 60-in. „	40—50
„ 30-in. cutting 16-in. pine ..	14
„ 48-in. cutting 18-in. teak ...	24
Band, hand-feed	2—5
„ heavy logs	20—40
Rip, 6-in. hardwood	15
Fret, up to 8-in. depth of cut ...	1—2
Frame	25—50
Cross-cut, small	2—5
„ heavy	15-20
Planers, small	1—3
„ high-power	10—15
General joiners	4—6
Mortising machines—	
Light	2—4
Heavy	10—15
Chain mortisers	4—8
Tenoning machines	5—10
Boring machines	8—15
Moulders	3—8
Pattern-maker's lathes	2—3
Flooring machines	20—30

MACHINERY.	H. P.
Deal-splitters	15
Graining machines	15
Sandpaper machines	2—4
Saw-sharpening machines	$\frac{1}{2}$—$1\frac{1}{2}$
Moulding iron girders	$\frac{1}{2}$—$1\frac{1}{2}$

FARM MACHINERY.	H. P.
Small threshers	3—6
Larger threshers, with complete cleaning gear	15—30
Clover hullers	15—20
Bruising mills	3—10
Root-cutters	$\frac{1}{4}$—1
Cake-breakers	1—2
Bone mills	$1\frac{1}{2}$—3
Chaff-cutters	2—5
Ploughs, 6 to 14 ins. deep	40—90
Irrigation pumps	10—20

FLOUR MILLS.	H. P.
Roller mills—	
10 bushels per hour	7—10
25—30 " "	18—22
Stone mills—	
2-ft. stone	6
4-ft. "	20
Fine flour combination machines, per 100 lbs. per hour ..	4—7

VENTILATING MACHINERY	H. P.
Fans.	
To move 1,000-1,500 c. ft./min ...	$\frac{1}{8}$—$\frac{1}{4}$
" " 3,000-6,000 " " ...	$\frac{1}{2}$—$\frac{3}{4}$
" " 6,000-9,000 " " ...	$\frac{3}{4}$—$1\frac{1}{4}$
" " 20,000-45,000 " " ...	$1\frac{1}{2}$—$3\frac{1}{2}$

167. Induction Generator

Principle :—This is simply an induction motor driven above its synchronous speed. We have seen that the speed of the rotating field of an ordinary squirrel-cage motor is slightly greater than the speed of the rotor. The slip of the rotor makes the magnetic lines of force cut the conductors, thereby inducing voltages, which cause currents to flow in the rotor circuits. The reaction between the rotating field and rotor currents transfers energy from the stator to the rotor. The magnetic flux is, therefore, the connecting link by which electric energy is transferred from the stator circuit and transformed into mechanical energy in the rotor.

If the rotor of the induction motor be belted to a direct-current motor or any prime mover whose speed can be varied, and stator be connected to the mains of the supply circuit, and if the speed is increased until the rotor runs in synchronism with the rotating field, no voltage is induced and no current flows in the rotor circuits. The energy necessary to overcome the friction and windage comes from the prime mover ; and the energy disappeared by the losses in the stator is supplied from the supply mains. If the speed is still further increased, the rotor revolves faster than the fields, or above synchronism, voltage is again induced and the rotor currents flow in the opposite direction from what was the case when operating below synchronous speed. If the rotor currents are reversed with respect to the field, the resulting reaction is also in the opposite direction, or energy flows from the rotor to the stator. Hence, when operating above synchronous speed, the mechanical energy supplied to the rotor is transmitted magnetically across the air-gap and delivered as electrical energy in the stator circuit. At speeds above synchronism, therefore, the induction motor is a generator, and transfers and transforms the mechanical energy from the prime mover into electric energy in the stator or primary circuit.

Primary Frequency:—In induction motor the rotor slip depends on the load, but variation in load and slip does not affect the primary frequency. When the machine is operated above synchronism, as a generator, the amount of power transmitted depends on the excess over synchronous speed ; but the relative rotor speed does not affect the frequency in the stator circuit.

Hence, if operated in parallel with ordinary alternators, the speed of the rotor varies with the load, and the machine does not run in parallel with other machines. The frequency of the current in the stator of the induction generator is the same as for the other alternators, and the division of the load depends upon the governors of the prime movers.

Excitation:—The induction generator is not self-exciting. It requires a wattless exciting current for its operation and cannot, therefore, be operated as a self-contained unit and runs only in connection with synchronous machines, generators or motors. These machines will then furnish the necessary excitation and also entirely govern the voltage and frequency of the induction generator.

The reactive energy of the rotating magnetic field must be supplied from an outside source to the stator winding. When operating in parallel with other alternators, delivering power to constant-potential mains, the exciting current automatically adjusts itself to the requirements for variation in the load. The power component is supplied through the rotor by the prime mover of the induction generator, but the quadrature component or reactive power, required for the magnetic field, comes from the other machines through the mains. Hence, whether operating as an induction motor or an induction generator, the reactive power in the stator circuit must be supplied from an outside source.

Operating in connection with over-excited synchronous motors is a desirable arrangement for induction generators as well as for induction motors. The required reactive power could be supplied by static condensers. The reactive power would oscillate between the condenser

and the field of the induction generator with double the frequency of the voltage, appearing alternately, in the magnetic field of the generator and the dielectric field of the condenser. The cost of the condensers would, in many cases, prohibit the use of this arrangement in commercial plants, since the required reactive power is approximately 25 per cent. of the generator capacity.

The no-load exciting current of large high-speed induction generator may be as low as 12 per cent. of the load current. The full-load reaction component or full-load excitation is sometimes as low as 25 per cent, which means a power factor of $1/\sqrt{1+(0{\cdot}25)^2} = 0{\cdot}97$.

Capacitor Excitation :—With capacitor excitation induction generator acts very much like a direct-current shunt wound generator, except that it has a separate characteristic curve for each power factor. The amount of capacitance required for excitation of a large induction generator is very high, so it is uncommercial.

Voltage Regulation.—When excited from synchronous machines it has no inherent regulation to voltage since in this respect it is quite as passive as an induction motor and depends wholly upon the voltage and corresponding excitation supplied to it by the system.

Frequency Regulation :—If the frequency is kept perfectly constant by the synchronous machines, induction generator can only deliver an increased output by increasing their speed and slip. If, however, the speed of an induction machine is kept constant, it can deliver more load only by a decrease in frequency, *i.e.*, by a decrease in the speed of the synchronous machines associated with it, such as synchronous generators or synchronous condensers.

Division of Load :—If the induction generator be driven by a prime mover with its governor so adjusted that the speed will drop slightly with the load, the frequency, and, therefore, the speed of the synchronous machines, must drop still more. Another method of dividing the load is to drive the induction machine with an ungoverned prime mover, *e g.*, a steam engine with fixed cut-off. In this case its output will be constant ;

and the speed-governed synchronous machine or machines will assume the load fluctuations; and the frequency regulation will be the same as that of the synchronous machines.

***168. The General Transformer (Vide Arts. 136, 151 and 152):**—In the stationary transformer the voltage is raised or lowered, but the frequency remains the same in the two circuits. The electric energy received in the primary is transmitted by the magnetic circuit to the secondary and transformed to electric energy at a higher or lower voltage but without change of frequency. In the induction motor the electric energy received in the stator is transmitted by the magnetic field across the air-gap and transformed into mechanical form and delivered through the rotor to the load. From the slip-rings of a wound-rotor induction motor, electric energy may be obtained in the same manner, as from the secondary of the stationary transformer. Connecting the slip-rings to an outside electric circuit the machine is both a motor and a transformer; and both mechanical and electrical power may be obtained simultaneously. The frequency of the voltage and current in the secondary circuit from the slip-rings need not be the same as in the stator, but depends upon the relative speed of the rotating field and the rotor. If the rotor is stationary, the frequency of the secondary current from the slip-rings is the same as in primary, and the machine is a stationary transformer with a large leakage flux.

Let the speed of the rotor be controlled independently of the rotating magnetic field, by belting to a variable speed motor which can operate in either directions. If the rotor revolves in the same direction as the stator field, the frequency of the current in the slip-rings is proportional to the difference in the speeds. If the rotor is forced to rotate in the opposite direction, that is, backward, the frequency of the secondary current is proportional to the sum of the speeds. Hence, if the backward rotation is considered negative, the frequency of the secondary currents is, in all cases, proportional

* Alternating Currents by C. E. Magnusson.

to the algebraic difference in the speeds of the rotating field and the rotor.

f_1 = frequency of the primary or stator circuit.
s_1 = speed of primary or rotating field
f_2 = frequency of the secondary or rotor slip-ring circuit.
s_2 = speed of the rotor.

$$f_2 = f_1 \frac{(s_1 - s_2)}{s_1}.$$

The voltage in the secondary depends upon the relative number of forces in the stator and rotor circuits and upon the relative speeds.

Neglecting losses in the machine,

$$E_2 = E_1 \frac{n_2 (s_1 - s_2)}{n_1 s_1}$$

Let X_s = reactance of the secondary circuit at standstill, and X_2 the corresponding reactance at speed s_2

$$X_2 = \frac{s_1 - s_2}{s_1} X_s$$

$$\dot{I}_2 = \frac{\dot{E}_2}{Z} = \frac{\dot{E}_1 \frac{n_2}{n_1} \left(\frac{s_1 - s_2}{s_1}\right)}{R_2 + j X_s \frac{(s_1 - s_2)}{s_1}}$$

The power relations of the general circuits or the direction of the energy-flow depend upon the relative speed of the rotating field and rotor. The reactive power, for both the stator and the rotor circuits, comes from the primary mains at all rotor speeds.

The reaction between the rotor field and the rotor currents necessarily consists of two equal and opposite forces; with the forces equal, the work done by the field or by the rotor is directly proportional to their speeds.

Neglecting losses in the machine, the power and speed relations may be grouped into four divisions.

1. For rotor speeds above synchronism

$$s_2 > s_1.$$

The machine is an induction or a synchronous generator, and the mechanical power supplied through the rotor pulley is transformed into electric energy in both the primary and secondary circuits. The relative frequency in the two circuits is given in the equation

$$f_2 = f_1 \frac{s_1 - s_2}{s_1}.$$

2. For speed between standstill and synchronism

$$0 < s_1 < s_2.$$

The total power is supplied from the primary circuit. The rotor delivers mechanical power. The frequency of the current in the rotor circuit is proportional to the slip ;

$$f_2 = f_1 \frac{s_1 - s_2}{s_1}$$

3. At standstill,

$$s_2 = 0.$$

With both windings stationary the machine operates as a stationary transformer. On account of the large air-gap the magnetising current is comparatively large ; but all the power is supplied by the primary and appears in the electric form in the rotor secondary. Here—

$$f_2 = f_1.$$

4. With the rotor running backward,

$$s_2 < 0.$$

The machine is a combination of generator and transformer. Electric energy is received from the primary and mechanical energy through the rotor pulley. From both sources the energy-flow is through the rotor and slip-rings to the secondary circuit. The frequency of the secondary circuit is greater than in the primary and equal to the sum (algebraic difference) of the speeds.

s_2 is negative,

$$f_2 = f_1 \frac{s_1 - s_2}{s_1}.$$

In cases 2 and 3 all the losses in the machine are supplied from the primary circuit. In case 1, near

synchronous speed and until the mechanical power supplied through the pulley is equal to or greater than the losses, the difference comes only from the primary circuit. In case 4 the losses are supplied from both circuits.

With a single winding on the rotor a single-phase current is delivered through the slip-rings. From a rotor-wound polyphase, the corresponding polyphase currents are delivered from the slip-rings. The machine can be used as a phase transformer since the secondary winding is independent of the primary. (See phase-advancers).

The extreme flexibility of a machine consisting of a primary and a rotating secondary is apparent. The general transformer can operate as a motor, generator, transformer, phase converter or frequency changer and may even perform most of these transformations simultaneously.

Output :—This depends on its speed above synchronism, and with the speed of the induction generator constant, it can only be increased by decreasing the speed and thus the frequency of the synchronous machinery.

169. Comparative Capacity of Induction and Synchronous Generators :—Induction generator cannot furnish any wattless exciting current for the inductive load on the system or for its own excitation. The current is supplied by the synchronous machine, thus necessitating an increase in their capacity.

Example 33. A system carries a load of 1,000 kW., 0·80 P.F. and that it is desired to install an induction generator of 5,000 kW., 0·95 P. F. What would be the required capacity of the synchronous generator.

Solution :—The wattless components of the load and the induction generator, which the synchronous generator must supply, will be 7,500 K.V.A. and 1,560 K. V. A., respectively; and, as in addition they must furnish the remaining energy of 5,000 kW., their capacity would have to be

$$\text{K. V. A.} = \sqrt{5{,}000^2 + 9{,}060^2} = 1{,}030$$

or twice that of the induction generator, and the power factor would be very low. A somewhat larger generator could, therefore, carry the entire load without any induction generator.

For higher power factor the condition would be different. If the power factor of the load, for example, were 0·95 instead of 0·80, the total wattless K. V A. to be supplied would be 3,288 + 1 560 = 4,848, and the capacity of the synchronous generators, in

$$\text{K. V. A.} = \sqrt{5{,}000^2 + 4{,}848^2} = 6{,}965$$

For low power factor it is, therefore, not very advantageous to use induction generator.

Operation :—When putting an induction generator into operation, it is only necessary to bring it up to speed and close the switch. Synchronising is not needed ; for, the machine cannot generate any E.M.F until excited from the line, and, when so excited, it will, of course, be in phase.

The first current rush is only exciting current, because the load cannot be picked up until the field is established. If the current-rush is undesirably large, it can readily be reduced by inserting reactances when the machine is thrown on the circuit. These coils can then be cut out as soon as a steady condition is reached.

When driven by governor-controlled water wheels, the speed of the induction generator will drop slightly with the load, and in order to divide the load properly it will be necessary for the speed of the synchronous generators to drop still more. The best method of operating induction generator is, therefore, to drive them with wheels without governor control. In this manner their output will be kept constant and the load fluctuations will be taken care of by the synchronous generators.

If a motor, to be operated as an induction generator, is thrown upon the line below synchronous speed, the machine first takes current from the line to come up to synchronous speed as a motor, the motor driving the water wheel for the time being. Under these conditions

there is a rush of current from the line corresponding to the starting of an induction motor under load and the line is subjected to a temporary surge.

If the motor is thrown on the line at exactly synchronous speed or very slightly above it, no effect is evident and no change is audible.

If thrown upon the line, at considerably above synchronous speed, the hum of the generator drops to a much lower pitch, and if the speed is too high, the circuit-breaker will at once release.

170. Care and Maintenance of Motors :— An electric motor requires very little attention to keep it in good working order. Given periodical cleaning and lubrication together with an occasional inspection to ensure that all is correct, a motor will work for many years without trouble. The only vital point regarding the maintenance of electrical machinery is that every operation and adjustment should be carried out along approved lines. This is essential because of the fine clearances and delicate insulating material which are necessary to be used in the manufacture of efficient machines.

Cleanliness :—Cleanliness is one of the first essentials for trouble-free service and long life. Insulation failure is generally due to presence of moisture, oil, grease, dirt or dust, and these injurious matters are mostly responsible for many mechanical troubles, *e.g.*, bearing troubles. Hence, every precaution is taken in the shops to prevent such troubles, to prevent water dripping on the motors or other machinery from a leaky roof ; and the removal of oil or grease dripping from the bearings is promptly attended to. Every machine is dismantled and thoroughly cleaned, most of them once in a year, *e.g.*, machine shop motors, overhead crane motors and some once in six months, *e.g.*, smithy shop motors, where much of dust and dirt are flying. Once in a week—on all Sundays when the shops are closed—the overhauling business is undertaken, thus giving the turn to the particular motor for the next period (12 months or 6 months).

But all the machines are freed of all loose dust and dirt by blowing compressed air or from a hand blower. This is done almost every week keeping the machine in a reasonably clean state, so that when the time comes for annual dismantling there is very little loose dust. The weekly blowing out is done by removing one or more of the covers which are screwed (or hinged) to the end brackets of the motor. The air blast is directed on the end windings and ends of core and is continued until the flying of dust ceases. If there is any leakage of oil or grease from the bearings, it is carefully removed and brush gear (of D. C. motors and slip-rings) are inspected and cleaned, as explained later. This weekly cleaning is not practised on totally enclosed motors. However, dirt, if any, adhering to the outside of the motor is cleaned and bearing examined as usual (of course, the brush gear requires weekly cleaning to all motors). Fan-cooled motors (mostly A. C. types) mostly have two flows of cooling air, one driving the external air through a series of cooling passages in the stator core and the other driving air through the back of the stator punchings. The outer fan is cleaned every week and the annual inspection is quite enough for the machine.

Hence, for the weekly superficial cleaning, the three things to be noted are—

(1) removing of all loose dust and dirt,
(2) cleaning of oil or grease that has exceeded from bearings,
(3) inspection and cleaning of brush gear.

Insulation tests are taken by means of a megger, and recorded. Radial air-gaps are measured by means of a feeler gauge.

Overhauling of Motors :—The dismantling procedure is very easy. When the machine is of ball and roller-bearing type, it is not opened or disturbed in any way; but ordinary bearings are dismantled and annually attended to. The internal leads of the motor or machine after removal are carefully marked by slips of paper and numbered with a duplicate at the original contact—thus avoiding troublesome cross-connections.

No unnecessary force is employed to dismantle or for subsequent assembly ; and hammer blows, as far as possible, are dispensed with.

When the motor is completely dismantled, each part is carefully cleaned of all dirt, oil or grease. Petrol is used to remove hardened grease, if necessary—even on windings where it is thinly coated. All air ducts in stator and rotor are carefully cleaned out and all exposed portions are also similarly attended to. Next a careful inspection is made to ensure that there are no signs of excessive wear or damage ; the bearings are examined for signs of scoring and the cast parts for cracks or signs of damage ; and the damages are rectified.

After taking the insulation resistance test of the windings and found O. K., a good quality of insulating varnish is applied to the end windings and all exposed insulation. Ordinary varnish or black enamel is very unsuitable for the purpose, and will damage the insulation. The varnish must be, of course, from a reputed firm (Shalimar air-drying enamel paint). This shiny coating of varnish does not allow dust to adhere and it assists, therefore, in the weekly blowing out.

When after inspection the insulation on one or other of the motor windings be found damaged (sometimes during dismantling slight damages are done), it is best to fit entirely new insulation, but may be repaired if the damage is of, say, the end-winding or coil insulation. If, then, the insulation resistance is low, the new insulation must be liberally soaked with varnish and tested to suit for service. For further troubles it is sent for rewinding to the repair shops.

After all the parts have been cleaned and new parts, if any, replaced, and when it is ascertained that they are all in good order, reassembling is proceeded. After the mechanical fitting is done, all internal leads and cables are connected to the terminals which they originally occupied—**care** !! The insulation is then tested again. When it is found to agree with the specified data, the air-gap is checked. This is also one of the monthly procedures, as said before—which is done by a special

narrow long feeler gauge. If they are different at points (less than 75 % of the other point) diametrically opposite, the correct alignment in the end brackets or bearing housings is set. Or at times two bracket-fixing screws become loose or bearings worn. All these result in the discrepancy of the gap, and if this is neglected, rubbing between stator and rotor will ensue causing excessive damage.

The control gear also is inspected and maintained at the same time as the motor receives attention. All contacts and connections are kept *clean and tight* and the gear is kept free from dust or dirt. Trip gears are operated once in a week to ensure that they work all right; arcing at contacts is reduced to minimum and the oil, if any, in the immersed gears, is filtered, contrifuged or entirely replaced, if needed.

At the time of *annual overhauling* very good care must be taken of the bearings in fitting and replenishing with oil of the quality recommended by the makers. The most common type of bearings on the shop motors are equipped with rings running on the shaft and dripping into an oil well. The rings must not split any oil and must be running freely picking up plenty of oil during the running. If the wells are very dirty, they are cleaned out being swilled with petrol. When the bearings are worn out, it is found that the bearings and shaft are rough or scoured; there will be excessive "play," "lift" or clearance between the shaft and bush, the air-gaps cannot remain equal. The bearings, therefore, are sent for relining and new bushes placed. An overheating bearing will almost invariably be detected when the motor is running at full speed on full load; and it is essential to correct the fault immediately, otherwise a seizure causing grave mechanical damage or fire may result. In such cases, the gearing or belt is removed, the speed reduced, if possible, and large quantities of oil poured directly on to the bearing shell through the lubricating passage. On no account the motor should be allowed to stop revolving until the bearings can be touched by hand; neglecting this, a seizure will ensue, causing burning or melting of the bearings. As soon as

the machine is stopped, the bearing is dismantled and the lining and shaft inspected for damage.

For ball and roller bearings the grease is introduced by means of a screw-down lubricator or a grease-gun. A comfortable warmth to the hand, when placed on the housing or cap, indicates that the bearing is running under the best conditions. If the temperature begins to rise, or if the bearings become noisy, an inspection is made immediately.

Brushes, Brush Gears, Slip-Rings and Commutators :—The brush gear is cleaned every week being wiped down with a clean cloth free from fluff. All carbon or metallic dust, oil or grease is removed carefully and the recesses, and particularly insulating surfaces, are kept very clean. All dust is removed from the spaces between the slip-rings and from the ends of the slip-rings, brush or commutator Vee rings. This periodical cleaning is essential to avoid constant break-down. Every week during the cleaning time each brush is lifted up against the spring pressure and then released. Any sluggishness of movement of the brush towards remaking contact is corrected immediately, otherwise destructive sparking and burning will set in and spoil the contact surfaces. Seizure is due generally to dust in the brush box or hinge bearing of the brush-holder and removal of this frees the brush. At the time of complete overhauling the brush pressure is tested by means of a spring balance and during the weekly cleaning the springs are tested by hand. Sometimes it is found that due to vibrations of the machine there is sparking and dancing of brushes The cause of the vibration is examined and rectified and the sparking is thus cured. At times a larger brush pressure is necessary (moderate —2 to $2\frac{1}{2}$ lbs./sq. inch for carbon brushes, 3 to $3\frac{1}{2}$ lbs./sq. inch for metallic brushes—and on no account the pressure is increased beyond $4\frac{1}{2}$ for carbon and $5\frac{1}{2}$ for metallic brushes) to cure this but, if it is found useless, the pressure must be released to normal. For removal of brushes there is no hard and fast rule. However, they are removed when it becomes less than $\frac{1}{2}''$ deep or when it becomes so short that no further spring pressure is available. At times

it is found that the wearing out of brushes is unequal resulting in sparking. This trouble may be due to unequal brush pressure, bad bedding, vibration, etc., and when these are rectified, the trouble will be no more. Where the brushes are renewed, they must be carefully examined to find whether they are broken or are of the same size and number as instructed by the makers of the motor. Next the old brushes removed, the holderscleaned and new brushes inserted—carefully examining that they slide in the holders freely. The spring tension is adjusted to the correct amount and this being done, the "bedding" of the brush proceeded. A strip of glass paper (not emery paper) is taken and placed in between the brush contact face and the commutator (or slip-ring), the rough side of the glass paper being outermost (*i.e.*, in contact with the brush) and the strip is drawn backwards and forwards so as to cut the brush face similar to that of the commutator. This is continued until all the brushes come to the exact surface—well-grounded—tested by lifting the brush ; and the dust is blown out.

Slip-Rings :—When the slip-ring is in a good condition it is smooth and highly polished on its contact surface, the color being of a bronze tint. The rings, their supports and insulation are kept neat, clean and free from dust so as to avoid leakage, flashing, etc. If the rings become roughened or scoured, they are cleaned up by means of glass paper when the damage is only slight, while a suitable commutator stone is employed for greater roughening ; when the rings are very badly spitted, they are turned in a lathe to smooth. If the brushes are noisy, giving high-pitched squeaking noises, when the slip-ring is in a perfect condition, a piece of rag moistened with a few drops of oil is run once round each ring.

Commutators :—In the case of D. C. or A. C. commutator motors, if the commutator is properly maintained, it is the most reliable of all the parts of the motor. It is very dangerous, and definitely so, to permit even the slightest accumulations of dirt on a commutator, because of the high potentials which exist between closely adjacent surfaces. In order to keep the commutator clean it is

necessary to wipe the contact surface with a clean cloth which is free from fluff, and slightly moistened with a few drops of oil to provide a slight lubrication. This should be so little as not to allow the accumulation of dust, etc.

The use of emery paper is strictly forbidden in grinding and hence a carborandum cloth is used for the purpose. A small carborandum cloth wrapped on to a block is pressed on the surface of the segments and the copper or other dust is blown out. If the commutator is badly worn, being rigid or burnt, its surface is turned up in a lathe; this may be avoided if it is possible to get rid of it by the carborandum cloth. To remove a flat from the surface of a commutator in a satisfactory manner the armature is taken out for at times the armature is nicely wrapped up so as to prevent any dust to enter in, if the former is not possible) and the shaft with commutator mounted on between the centres of a lathe. The surface is turned up with a keen tool which is firmly fixed in a slide rest. Heavy cuts are seldom taken, as the tool may dig in and cause bars to be displaced, and also produce heavy burrs on the edges of the bars. These burrs will be difficult to remove. The mica insulation will not be cut away if a heavy cut is taken, but it will be bent over between the surface of the commutator and the edge of the cutting tool. When all traces of the flat have been removed, the surface must be made perfectly smooth with a fine grained carborandum block or a piece of fine glass paper fixed to the end of a block of wood shaped to the curved surface of the commutator. All burrs are removed from the edges of the bars with a smooth file and all the copper dust is scraped out as this may be embedded in the surface of the mica insulation. The next thing is the *mica trouble!* High bars sometimes develop due to mechanical defects in the micanite Vee rings, and can often be located when the commutator is stationary, as the surface of such bars appears cleaner than the rest of the commutator. By heating the commutator by means of a gas ring up to a temperature well above normal working temperature (never more than 100° C.), then taking up any slackness of the commutator on the through bolts and grinding up the commutator, these

high bars are eliminated. If the high bars become pronounced, they often become in breakage of brushes and expensive replacement. At times, if need be, the seasoning of the commutator is done with the taking up of any slackness until no further trouble occurs. It is important that the tension applied to commutator bolts must not exceed safe limits, otherwise the bolts will become permanently injured or the commutator bar itself might be fractured. Blackening of the commutator is caused either by high mica or incorrect adjustment of the commutating poles. In cases of high mica it is usual practice to give an undercut, even otherwise, soon after the commutator is turned in the lathe ; an undercut of mica is given to a depth of 1/32″ nearly. Deeper undercut is dangerous since it may be filled up with carbon dust and result in a short circuit between segments. The usual practice of giving an undercut is by means of an undercutter fitted to a lathe or a hand saw—a hack saw blade riveted or slotted into a rod which, in turn, is fitted into a handle.

After the mica has been removed and all dust cleaned (this being done by wrapping the armature with a piece of canvas or paper well wrapped) from the commutator surface and mica grooves, the edges of the segments are very slightly bevelled with a smooth piece of hard steel so as to remove the sharp edge of the copper which is left when the mica has been undercut.

It is very important to note that oil and grease should not be permitted on any commutator and when the mica is recessed, the presence of these together with dust is particularly objectionable.

Exercises.

1. Explain how a rotating field is produced by means of a three-phase current and give reasons why, in an induction motor, it is desirable to have a sine wave supply voltage and also windings designed to give a sine distribution of magnetic induction over the polar arc. (Grade II., A. C., 1914).

2. State and explain the principle on which a three-phase non-synchronous motor works.

3. Describe the principle of action of a non-synchronous three-phase motor. Illustrate by a circle diagram. (Grade II., A. C., 1913).

4. On which points, in the design of a three-phase induction motor, does the power factor depend ? Why is a resistance inserted in the rotor circuit of an induction motor with slip-rings at starting ? How does an induction motor behave, if, without any alteration in its connections with the supply circuit, it is driven by mechanical power so that its speed is raised above that of synchronism ? (Ord., A.C., 1910).

5. Explain the terms " power factor " and " slip. " (A. M. I. E. E. Exam., 1914).

6. Describe the relative advantages and disadvantages of squirrel-cage and slip-ring induction motor. (A. M. I. E. E. Exam., 1914).

7. Explain the action of an induction motor. State the relative advantages and disadvantages of squirrel-cage and wound rotors, and describe, with diagrams. the methods used in starting motors of each type. (Grade II.. A. C.. 1912).

8. Describe the differences between a squirrel-cage and wound rotor, stating the advantages of each Give diagrams of connections for motor and starting gear in each case. (Wiremen's Final, 1914).

9. Give a diagram of connections for a three-phase auto-starter, and a diagram of connections for a rotor starter for a three-phase motor. (A. M. I. E. E. Exam., 1914).

10. Describe suitable methods of starting three-phase induction motors in the following cases :—(*a*) small squirrel-cage induction motors in factories, (*b*) large induction motor driving continuous current generator, (*c*) large induction motor operating haulage gears. (Final, 1st paper, 1914).

11. Explain why in a three-phase induction motor (*a*) the torque is approximately proportional to the slip, if the applied potential difference is constant ; (*b*) the

torque exerted for a given slip is proportional to the square of the applied potential difference. (Ord., A. C., 1911).

12. Explain why (*a*) in a three-phase induction motor the power wasted in the rotor circuit is approximately proportional to the square of the slip, (*b*) the starting torque of a motor with a wound rotor is increased by inserting resistance in rotor circuits.

(Grade II., A.C., 1912).

13. Explain why, in an induction motor, (1) the torque exerted by the motor is proportional to the slip ; (2) when the voltage at the motor terminals is varied, the torque exerted by the motor for a given slip is proportional to the square of the applied voltage ; (3) the air-gap of the motor must be short, if it is to have a good power factor. (Grade II., A.C., 1913).

14. What modifications are necessary in the design of a continuous-current series motor, in order to make it suitable for running with alternating current (single-phase)? How does the frequency affect the power factor and the limiting output of a motor of that type? (Honours, 1st paper, 1910).

15. Explain, with the help of a diagrammatic representation of the windings and circuits, the construction and mode of operation of a modern form of single-phase repulsion motor suitable for railway work. Give the speed-torque curve of such a motor, and describe the means employed for starting and speed regulation. (Honours, 2nd paper, 1910).

16. Explain, with sketches, the construction and principle of action of some of single-phase commutator motors. Why is commutation more difficult in a single-phase series motor than in working on continuous current? (Honours, 1st paper, 1911).

17. A two-phase motor fed by three conductors takes 60 amperes in each outer conductor. The voltage of each phase, *i.e.*, between the common middle wire and the two outers, is 200 volts. Calculate the horse-power developed, the current in the middle wire, and the voltage across the outers. Efficiency, ·86 ; power factor ·86. (Wiremen's Final, 1912).

18. Calculate the current in the conductors supplying a three-phase motor developing 10 B. H. P. at 400 volts. Efficiency of motor 85 per cent., power factor 85 per cent. (Wiremen's Final, 1911).

19. An installation of four 10-H P. and one 35-H. P. motors, and 100 40-C. P. metal filament lamps is to be supplied from a public supply 3-phase 4-wire main. The pressure across phase is 380 volts, and the lighting is to be, as near as possible, balanced between phases and neutral. For what pressure must the lamps be supplied; and what must be the section of each core of the service main, neglecting drop in volts? (A. M. I. E. E. Exam., 1914).

20. The resources of a work are not sufficient to test a large induction motor under full load. What tests can you make on that motor to predict with a fair degree of approximation its power factor at different loads? (Final, 2nd paper, 1914).

21. Construct, and explain fully, the circle diagram of the induction motor, showing in particular the manner in which the performance on load of an induction motor can be completely determined with the help of this diagram and certain no-load measurements. (Honours, 2nd paper, 1911).

22. What is the "circle-diagram" of a three-phase motor and why is it given that name? Show a typical diagram for a three-phase motor, and explain how the current, power factor, slip, torque, and power are found from the diagram. How would the diagram change if the motor had more magnetic leakage? (Grade II., A. C., 1914).

23. Show a typical circle diagram for a three-phase motor, including the graphic representation of current, power factor, slip, torque and power. How would the diagram change if the motor had more magnetic leakage? (Ord., A. C., 1911).

24. Describe the working parts of a three-phase induction motor. Two such motors, identical in every other respect, have different width of air-gap. How will they differ from one another in their performance

under identical conditions, in respect of current, power factor, slip, and torque, at normal-load, at no-load, at over-load, and at starting ? (Ord., A. C., 1909).

25. A certain three-phase slip-ring induction motor, rated at 45 B. H. P., 400 volts, 50 cycles per second, and 1,500 R. P. M. no-load speed, is tested running light, with the following results :—

No-load current at 400 volts, 50 cycles=17 amps.
Energy absorbed at do. do. = 1,600 watts.

The motor was then tested at standstill with short-circuited rotor, when it was found that the stator current at 100 volts was 80 amperes, the power factor of this current being 0·25, the resistance per phase of the stator winding (measured warm) was 0·15 ohm.

With the help of a vector diagram, pre-determine close approximate values for :—

(*a*) The full-load current ;
(*b*) Full-load power factor ;
(*c*) The over-load capacity of this motor, when running under normal conditions.

(Honours, 2nd paper, 1902).

26. A three-phase star-connected induction motor gives the following data on test at a frequency of 50 :—

Running light—6,000 volts, 39 amperes per phase.
Power taken—21 kW.
Rotar locked—1,200 volts, 128 amperes per phase.
Power taken—48 kW.

The resistance between any two of the primary terminals of the motor is 0·667 ohms. Assuming that the power taken by the motor when locked is proportional to the square of the voltage, find maximum power which the motor will give, and determine the slip. Take the supply pressure to be 6,000 volts at 50 frequency. (Final, 1st paper, 1914).

27. A three-phase induction motor takes, when running light on pressure of 120 volts, a current of 7·5 amperes per phase at a power factor of 0·29. When the rotor is clamped, the motor takes 24 amperes per phase with a

pressure of 24·5 volts at a power factor of 0·45. Find the maximum power at which the motor will operate and the load at which it will "pull out." (Final, 1st paper, 1913.)

28. Discuss the propositions which have been made for operating main line railways of full gauge with electricity at pressure exceeding 1,000 volts, and point out the considerations which are involved in the adoption of the particular types of motor, modes of motor control and means of collecting the current. (Honours, 2nd paper, 1908).

29. A 500-H. P., 440-volt, 50-cycle, 3-phase induction motor was tested and the following data obtained :—

	Stator Current per phase.	Watts input per phase.
Without load ...	190 ...	500
With rotor locked ...	2,700 ...	281,200

Stator resistance per phase=0·015 ohms.

Construct the circle diagram.

(2) From the circle diagram of the above problem plot the following curves :—(*a*) speed torque, (*b*) efficiency, (*c*) power factor.

(3) From the circle diagram determine the following when the output of the motor is 500 B. H. P. (*a*) current input, (*b*) torque developed in the rotor, (*c*) power factor, (*d*) speed, (*e*) added copper losses in stator, (*f*) rotor losses.

(4) Also determine (*a*) the stator current required to produce the maximum torque, and the value of this starting effort in synchronous horse-power, (*b*) the stator current and the torque when the power is maximum.

30. Explain the construction and action of a single-phase induction motor and describe a device for starting such a motor. (C. G. II).

31. A three-phase, 50-cycle induction motor with its rotor star-connected, gives 100 volts (root mean square) at standstill between slip-rings on open circuit. Calculate the current in each phase of the rotor winding

when joined to a star-connected circuit, each limb of which has a resistance of 10 ohms and a reactance of 10 ohms. The resistance per phase of the rotor winding is 0·2 ohm and its reactance at standstill 10 ohms. Calculate also the current in each rotor phase when the slip-rings are short-circuited and the motor is running with a slip of 4 per cent. (L. U., 1922).

32. Define the "slip" of a three-phase motor. Draw two curves connecting the torque of the motor with the slip for two different values of the resistance in the rotor circuits. State the connection between these two curves and give the theory of the curves. (L. U., 1915).

33. State the advantages of cascade control of induction motors for traction work. Define the term "cascade synchronous speed" (L. U., 1911).

34. Describe a method of obtaining, economically, speed regulation in the case of a large three-phase induction motor, the range over which speed regulation is desired being approximately synchronous speed to about 70 per cent. below synchronous speed. Describe briefly the apparatus required for this purpose, and explain its working. (L. U., 1921).

35. Show how to arrange two windings on the rotor of a three-phase induction motor to provide automatically large torque at starting and low rotor copper loss when running. How would you calculate the starting torque of such a motor ? (C. and G., 1923).

36. A four-pole, 50-cycle, three-phase, 200-volt induction motor is run on light load and takes 12·5 amperes per line at a power factor of 0·2. The same motor, when the rotor is allowed to rotate very slowly, takes 100 amperes when a pressure of 120 volts between phases is applied, at a power factor of 0·25. Estimate the pull-out torque and maximum power factor at which the motor will work ? (C. and G., 1918).

37. The speed of a 400 H. P. electrically-driven fan is reduced by—

(*a*) A shunt motor with field control.
(*b*) An induction motor with rotor resistance control.

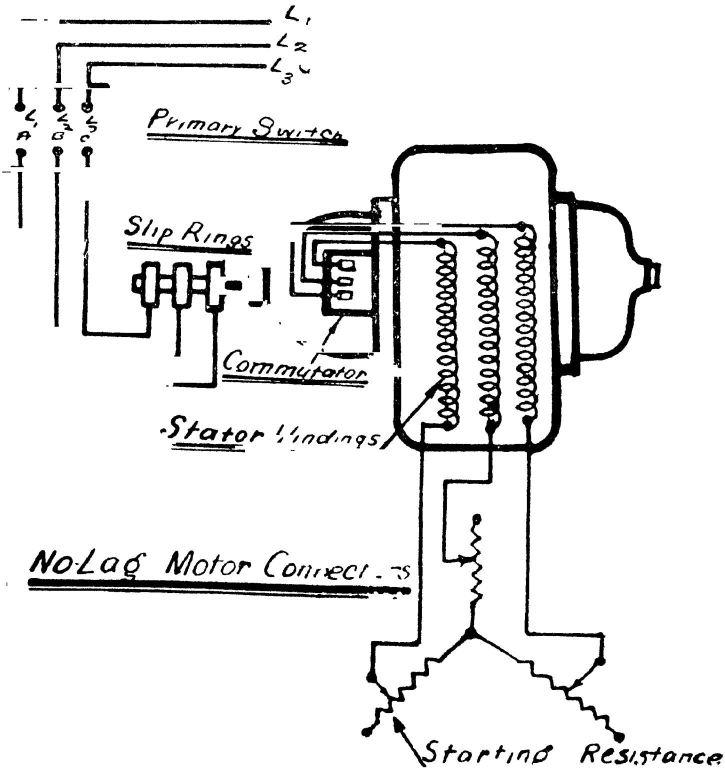
Compare the economy obtainable per hour in the two cases when the speed is reduced 15 per cent. Assume that the torque of the fan varies as the square of the speed and the cost of energy is 1d. per B. O. T. unit. Ignore losses in the motors. (C. and G., 1921).

38. How can the speed of an induction motor be varied by altering the number of phases ? Give any two methods of varying the speed of an induction motor by supplying the slip energy to machines possessing commutators. (C. and G., 1922).

Appendix to Chapter III

The "No-lag" Induction Motor :—

The "No-Lag" induction motor is a special type of induction commutator motor, and has its primary winding on the rotor and the secondary winding on the stator, *i. e.*, inverse to the usual arrangement in an ordinary induction motor. The leads from the supply are connected to the primary winding by means of slip rings on the rotor, *i. e*, the supply leads are connected to the slip-ring brushes. In addition to the primary winding, there is also a compensating winding on the rotor. This compensating winding is provided with a commutator, and by means of the brushes on the commutator, it is connected in series with the secondary winding on the stator.



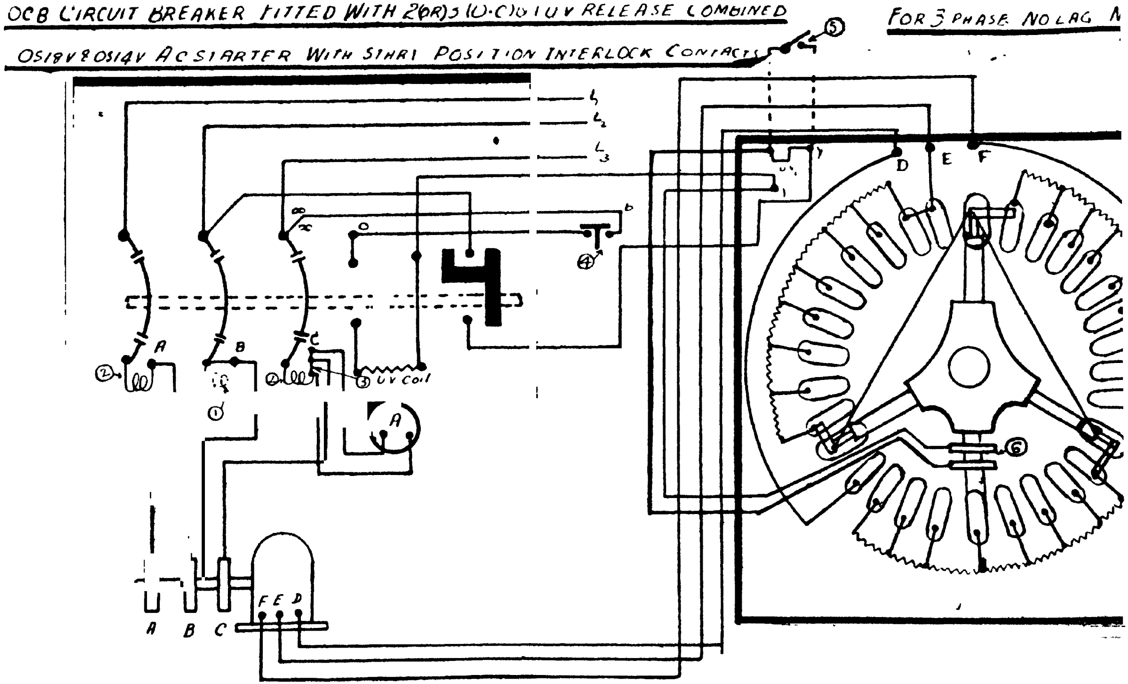

OCB CIRCUIT BREAKER FITTED WITH 2(OR)3 (O.C)(S) UV RELEASE COMBINED
OS18V & OS14V AC STARTER WITH START POSITION INTERLOCK CONTACTS
FOR 3 PHASE NO LAG M
L1
L2
L3
A
B
C
UV Coil
D
E
F
F E D
A B C

Fig. B

The advantage of this motor is that the power-factor can be varied to any value by varying the position of the brushes on the commutator. The correct position for the rated power-factor is set by the manufacturer, and the brush-rocker marked for both directions of rotation.

Starting:—Fig. A shows the internal connections of this motor, while Fig. B shows the oil switch and the starting resistance. This motor is started in the usual way by gradually decreasing the resistance in the secondary circuit. The stator is connected to the starting resistance as in Fig. B. The oil switch is provided with two overload coils and if the 3rd overload coil is also required, the connection (1) can be omitted, so that the overload coil, shown dotted, is also in circuit. '*A*' is an ammeter, which if required to be connected, the connection (3) is omitted. If a push button control is also required, the line L_3 is connected to X through the push button. An under-voltage coil is also provided.

A substantial masonry foundation, having a suitable footing is provided for the machine. The following are the operations for starting :—

(1) Before starting, see that the handle of the rheostat is placed in the "starting" position.

(2) Close the line switch and start up the motor by moving the handle of the rheostat from contact to contact allowing sufficient time on each contact for the motor to reach its steady speed. The total time occupied in moving from the first to the last contact should be from 15 to 30 seconds. If longer time is taken, the rheostat may get over-heated.

Safe starting time can be determined by inserting an ammeter in the circuit and noting the fluctuation when the starting lever is moved forward one contact ; the current will increase momentarily and will then settle down to a steady value, which should be approximately the full load current of the motor. Immediately this steady value is indicated, the rheostat arm may be moved

forward to the next contact and so on, until, all the resistance steps have been cut out.

Note :—Where liquid starters are used, the dippers should be entered in the solution before the line switch is closed. In shutting down, always open the line switch first

Drying out :—" After erection, and before putting a motor into service, a test should be taken of the insulation resistance. This is of special importance, where the bigger machines are concerned, the erection of which may have occupied considerable time. The insulation resistance should in no case be less than one megohm for the primary winding on the rotor, and for the secondary windings, brush gear, rotary regulating winding and commutator which form together one circuit, it should not be less than 0·2 megohm. If the tests indicate a lower insulation resistance, the machine must be carefully dried out before it is put into service." (B T. H. Co.).

Direction of Rotation and Reversibility :—In the case of motors operating on a 3-phase circuit, the direction of rotation can be reversed by changing any two of the primary supply leads. On a 2-phase, 4-wire circuit, one phase may be reversed, while on a 2-phase, 3-wire circuit, the two outers are interchanged to reverse the direction of rotation.

It is important to note that the brush position must be changed when the direction of rotation is changed. The rocker is marked for both rotations, and care must be taken to set the rocker correctly for the required direction of rotation. There are three lines marked on the hub to correspond with the arrow marked on the brush-rocker. When the rocker is set on the middle line, the brushes are on neutral, and very little power-factor improvement obtained. By shifting the brush-rocker in the direction of rotation, P. F correction is obtained. The rated P. F. of the motor is obtained when the brush-rocker is set on the outer line which corresponds with the direction of rotation. When the correct adjustment is made, the rocker is locked by the locking screw.

To face page iv

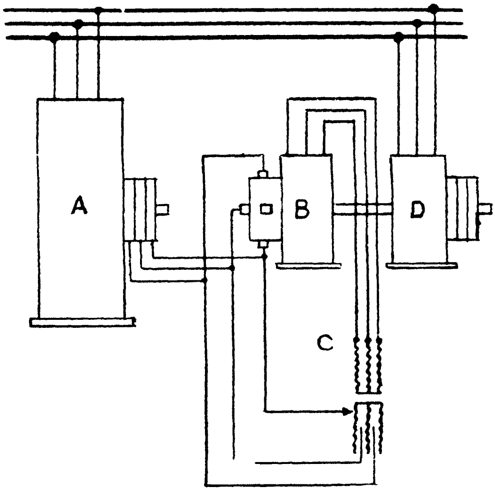
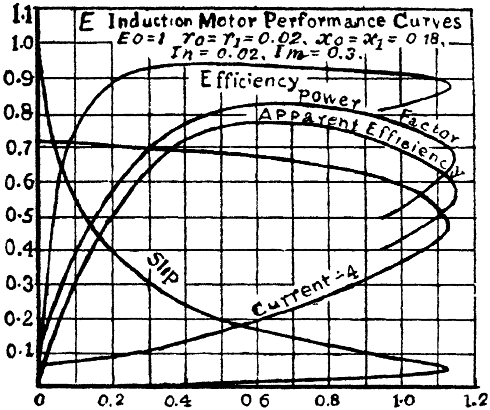


Fig. C

The Scherbious System of Speed Control :— Fig. C shows the arrangement. The main motor A, is a simple induction motor with slip rings. An auxiliary set on an independent shaft controls the speed. This set consists of a commutator motor B, driving an induction generator D. Instead of delivering mechanical power to shaft of the main motor the auxiliary machine returns electrical energy to the supply system. The amount of power transformed by the auxiliary set is controlled by the adjustment of the position of the taps in the transformer C, or rheostat if, an exciter is used. The greater the amount of energy absorbed by B, the lower will be the speed of the main motor A. The use of an independent high-speed set, which can be readily transferred to some other motor if subsequent conditions make the change desirable, is a distinct advantage.

Performance Curves of Induction Motors



Efficiency, Apparent Efficiency, Power Factor, Slip Current

Fig. 3·67

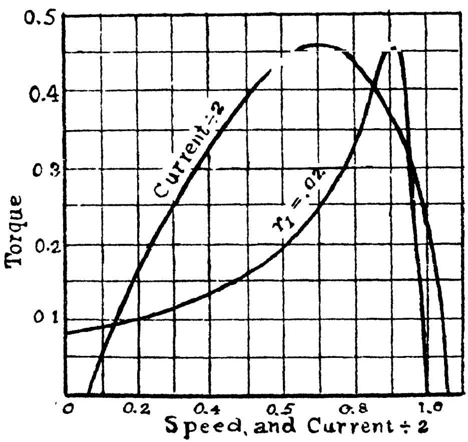
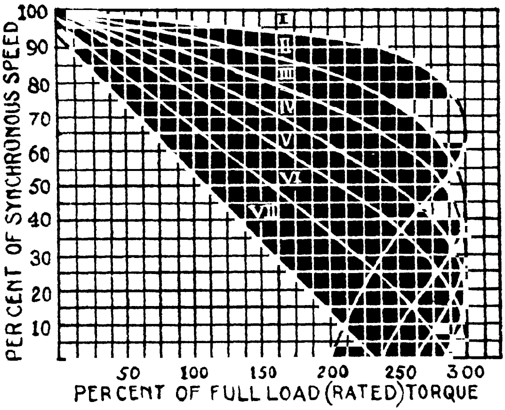
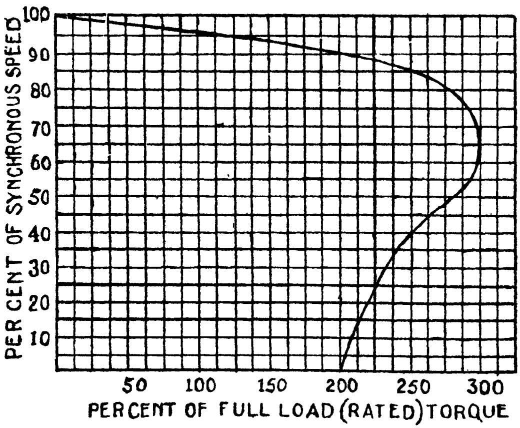


Fig. 3·68



Speed Torque Characteristics for Slip-Ring Induction Motor, Resistance of Rotor increased by Step.

Fig. 3'69



Speed Torque Characteristics for Squirrel-Cage Induction Motor

Fig. 3'70

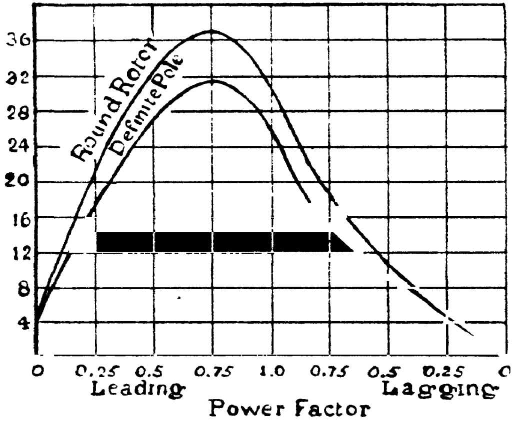

36
32
28
24
20
16
12
8
4
Round Rotor
Definite Pole
0
0.25
0.5
0.75
1.0
0.75
0.5
0.25
0
Leading
Lagging
Power Factor

Fig. 3·71

CHAPTER IV

CONVERTERS

171. Principle of Rotary Converters:—In a D. C. dynamo, the pressure and current produced in the armature coils are always of an alternating nature. By the addition of the commutator this A. C. is delivered to the external circuit as a unidirectional or direct current. If the two ends of the armature winding are connected to slip-rings, a single-phase A. C. would be available at the brushes resting on them.

In a rotary converter the ends of the armature coils at one end of the armature are brought out and connected to the segments of a commutator, thus producing a D. C. supply when the machine is excited and run up to speed, just as any D. C. dynamo. Tappings from the armature coils are taken at the other end of the armature, and the leads are connected to slip-rings fixed to the shaft. Alternate current is collected and distributed to the external circuit from these slip-rings.

Thus it is a "double-current" generator, and the same armature, when driven by some prime mover, produces both D. C. and A. C. The machine, when supplied at the slip-ring end with A. C., produces D. C. at the commutator ends; or if supplied with D. C. at the commutator end produces A. C. at the slip-rings. When the conversion is from A. C. to D. C., which is the more common use of the converter, the machine is called a *rotary converter*, or simply a *rotary*. The machine is running as an A. C. synchronous motor and generating as a D. C. dynamo.

In the second case, when it is running as a D. C. motor and generating as an *alternator*, it is called an *inverted* rotary.

The behaviour of an inverted rotary converter is different in many respects from the performance of the

same machine when used as a regular rotary converter. When converting from direct to alternating current, the speed of the converter will be proportional to the applied direct-current voltage, and will also depend upon the field excitation. The effect of weakening the field is to increase the speed. Hence, there should be no series field winding provided on inverted rotaries.

Application.—

(1) A D. C. generator or motor ;
(2) An A. C. generator or synchronous motor ;
(3) A double-current generator ;
(4) Ordinary rotary converter driven as a synchronous motor and delivering D. C. supply ;
(5) Inverted rotary, driven from D. C. supply and generating A. C.

172. Voltage Control.—(*a*) *Control of Direct-Current Voltage.*—Due to the fixed ratio between the alternating voltage and the direct-current voltage, variation in direct-current voltage can be obtained only by three general methods, which are as follows :—

(1) by varying the alternating voltage ;
(2) by varying the direct-current voltage ;
(3) by varying the flux without correspondingly varying the alternating voltage, as in the split-pole converter.

(*b*) *For varying the Alternating-Current Voltage,* the important commercial methods are :—

(1) by induction regulator or regulating transformer, or variable ratio, step-down or auto-transformer, or by using reactive leads ;
(2) by synchronous regulators or boosters ;
(3) by the combined action of reactance and series field winding, properly proportioned in connection with series inductive reactance by varying the wave-shape of the alternating current voltage.

Methods (1) and (2) of (*b*) are non-automatic and are used where the load is fairly constant over considerable periods as in lighting.

Method (3) (*b*) is entirely automatic within a range of 10 to 15 per cent. and is frequently used where the load is rapidly fluctuating as in electric railway.

Method (1) can be made to operate automatically.

Although in ideal conditions there is no voltage-drop in the armature, practically there is always a drop of voltage in the armature. Hence, with a constant impressed alternating current voltage on the rotary terminals or the supply generator, the drop in the armature or in the armature and the line causes a variation in the terminal direct-current pressure and in order to compensate for this drop in line and armature, the series field is compounded and the shunt field is under-excited, so that (1) at no-load the machine acts as a synchronous motor drawing a lagging current of about one-third the normal value; (2) at 3/4-load the current is in time phase with the voltage; (3) at full-load the current owing to the series field M. M. F. will somewhat lead and thus the terminal voltage is increased. The fixed ratio of voltage is a serious handicap in electric railways and similar work where it is desirable to have the station voltage increased as the demand for current increases in order that the voltage at the distant point of the line shall be kept up in spite of the increase in the line drop. Hence, in order to increase the voltage of the direct-current output of the converter, it is necessary to increase the alternating current voltage supplied to the collector rings. For railway work the voltage is controlled by variation of the phase current input and the machine is over-compounded to neutralise the drop in feeders.

173. (a) E. M. F. Relations for Rotary Converters :—Let E be the difference of potential between the direct-current brushes of a rotary converter; and let E_2, E_3, E_4, E_6 be the effective values of the alternating electromotive force, and I_2, I_3, I_4, I_6, currents between adjacent collecting rings of a two-ring, three-ring, four-ring, and six-ring rotary converter, respectively.

We now find the relationship between these various electromotive forces.

Relationship between E and E_2:—The maximum value of the alternating E. M. F. between the collecting rings of a two-ring converter occurs at the instant when the commutator bars, to which the collecting rings are connected, are in contact with the direct-current brushes, and the maximum value is, of course, equal to E. Therefore, the effective value E_2 of the alternating electromotive force between the slip-rings of a two-ring converter is equal to $\frac{E}{\sqrt{2}}$.

That is,

$$E_2=\frac{E}{\sqrt{2}}$$

Relationship between E_2 and E_3:—Suppose a direct-current ring armature has 18 conductors (Fig. 4·01), each conductor representing a turn of wire. Consider the conductor 1. This conductor has an alternating electromotive force induced in it as the armature rotates. Let this alternating electromotive force (effective value) be represented by the short line 1.

Consider the next following conductor 2. The alternating electromotive force induced in this conductor has the same value as that induced in conductor 1, but is behind it in phase by the angle $360°/18=20°$, where 18 is the total number of armature conductors. Let the electromotive force induced in conductor 2 be represented by the short line 2.

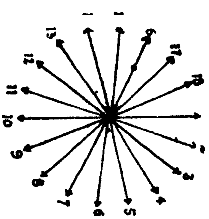


Fig. 4·01

Similarly, the short lines 3, 4, 5, 6, 7, etc., represent the alternating electromotive forces (effective values) induced in the conductors 3, 4, 5, 6, 7, etc.

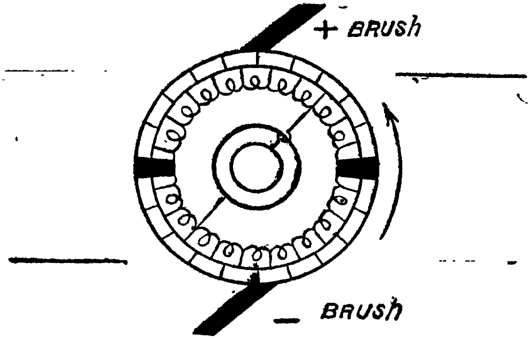
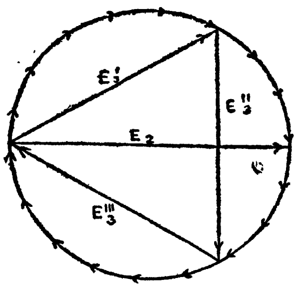


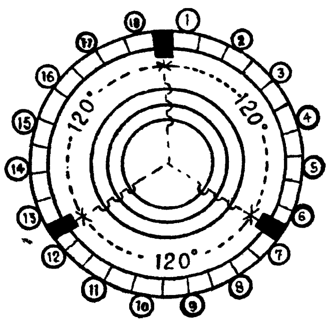
Fig. 4'02

Consider First the Two-Ring Converter:—Suppose that its slip-ring 1 is connected to the commutator bar which is between conductors 18 and 1. Then its other slip-ring will be connected to the bar, which, in Fig. 4'02, is between conductors 9 and 10, and the alternating electromotive force E_2 between these two slip-rings will be the vector sum of the electromotive forces 1, 2, 3, 4, 5, 6, 7, 8 and 9. That is, E_2 (effective value) is represented by the diameter of the polygon (circle).



The E. M. F. Relations in Two-and Three-Ring Converters.

Fig. 4'03



Brush and Commutator Diagram of Three-Ring Converter.

Fig. 4'04

Consider now the Three-Ring Converter:—Suppose its three rings are connected, as shown by the numbers 1, 2, and 3, in Fig. 4·04. Then, the electromotive force E_3, between rings 1 and 2, is the vector sum of the electromotive forces 1, 2, 3, 4, 5, and 6, as shown in Fig. 4·03; the electromotive force E_3'', between rings 2 and 3, is the vector sum of the electromotive forces 7, 8, 9, 10, 11, and 12; and the electromotive force E_3''', between rings 3 and 1, is the vector sum of the electromotive forces 13, 14, 15, 16, 17, and 18, as shown in the same figure.

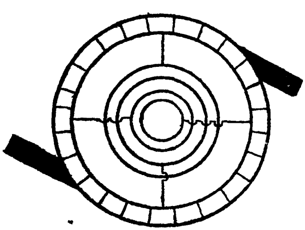
Therefore, the effective value of the electromotive force E_2 between the two rings of a two-ring converter, being represented by the diameter of a circle, the effective value of the electromotive force E_3, between any two rings of a three-ring converter, is represented by a 120-degree chord of the same circle. Therefore,

$$E_3 = \frac{\sqrt{3}}{2} \times E_2,$$

or, using the value of E_2 from the equation of Art. 173 we have

$$E_3 = \frac{\sqrt{3}}{2} \times \frac{E}{\sqrt{2}} = 0·612\ E.$$

It is to be noted that in order to make a direct-current machine into a three-, four-, or six-ring converter, the number of armature conductors must be divisible by the number of rings. Therefore, the armature shown in Fig. 4·05 is not suitable for a four-ring converter, although it is suitable for a three-ring converter.



Brush and Commutator Diagram for Four-Ring Converter.
Fig. 4·05

The foregoing discussion shows that if the effective value of E_2 is represented by the diameter of a circle, then the effective

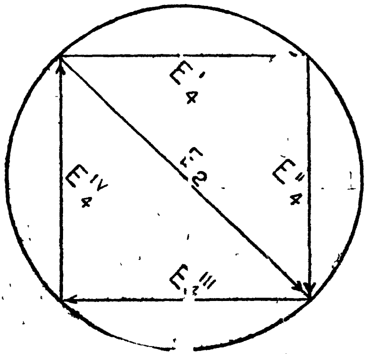
value of E_3 is represented by a 120-degree chord, the effective value of E_4 is represented by a 90-degree chord, and the effective value of E_6 is represented by a 60-degree chord of the same circle. This is shown in Figs. 4·06 and 4·07.

From Fig. 4·06, we have

$$E_4=\frac{E_2}{\sqrt{2}}$$

or, substituting the value of E_2 as before, we have

$$E_4=\frac{1}{\sqrt{2}}\times\frac{E}{\sqrt{2}}=\frac{E}{2}$$



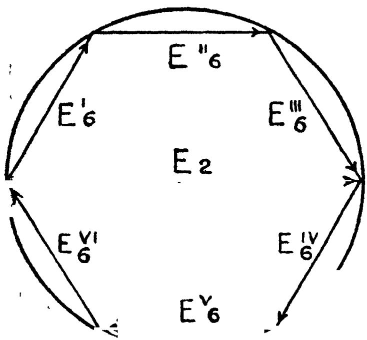
E. M. F. Rela' on in a Four-Ring Con' rter.

Fig. 4·06

From Fig. 4·07 we have $E_6=(1/2)\,E_2$, or substituting the value of E_2, we have

$$E_6=\tfrac{1}{2}\times\frac{E}{\sqrt{2}}=0{\cdot}354\,E.$$

Example 1. If a rotary converter is to deliver direct current at 2·25 volts:



E. M. F. Relation in a Six-Ring Converter.

Fig. 4·07

(*a*) It must be supplied with single-phase alternating currents at 159 volts effective, if it is a two-ring converter.

(*b*) It must be supplied with three-phase current at 137·7 volts effective between each pair of the three supply mains, if the converter is a three-ring converter.

(*c*) It must be supplied with two-phase currents over four-wire supply mains with 112·5 volts

effective between mains connected to adjacent collector rings ; or 159 volts effective between mains connected to opposite collector rings, if the converter is a four-ring converter.

(*d*) It must be supplied with six-phase currents over six-wire supply mains, with 79·6 volts effective between the mains connected to adjacent collector rings ; or with 137·7 volts effective between the mains connected to rings 1 and 3 ; or with 159 volts effective between the mains connected to opposite collector rings.

(b) Alternative method.—

Let E = the voltage between successive direct-current brushes.

E_n = effective voltage between successive rings of an n-ring converter.

e = the maximum E. M. F. in volts generated in a single armature inductor. This will exist when the conductor is under the centre of pole.

c = the number of armature inductors in a unit electrical angle of the periphery. The electrical angle subtended by the centres of two successive poles of the same polarity is considered as 2π.

The E. M. F. generated in a conductor may be considered as varying as the cosine of the angle of its position relative to a point directly under the centre of any north pole, the angles being measured in electrical degrees. At an angle θ (Fig. 4·08), the E. M. F. generated in a single inductor is $e \cos \theta$ volts. In an element $d\theta$ of the periphery

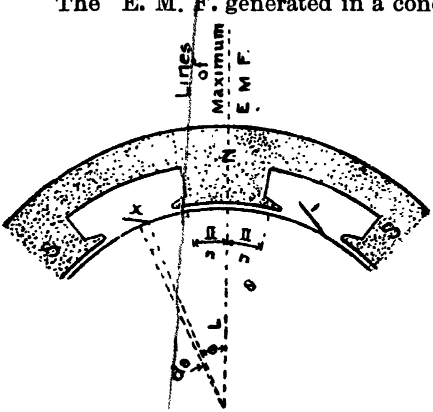


Fig. 4·08

of the armature there are $c\,d\theta$ inductors, each with this E. M. F. If connected in series they will yield an E. M. F. of $e\,c\cos\theta\,d\theta$ volts. The value of e can be determined if an expression for the E. M. F. between two successive direct-current brushes be determined by integration, and be set equal to this value of E as follows :—

$$E=\int_{-\pi/2}^{+\pi/2} e\,c\cos\theta\,d\theta=2\,e\,c.$$

$$\therefore\quad ec=E/2.$$

In an n-ring converter, the electrical angular distance between the taps for two successive rings is $2\pi/n$. The maximum E. M. F. will be generated in the coils between the two taps at an equal angular distance from the centre of a pole, one on each side of it, as shown in the figure. This maximum E. M. F. is

$$\sqrt{2}\,E_n=\int_{-\pi/n}^{+\pi/n} ec\cos\theta\,d\theta=2\,ec\sin\pi/n.$$

The effective voltage between the successive rings is, therefore,

$$E=\frac{E}{\sqrt{2}}\sin\pi/n.$$

By substituting numerical values in this formula, it is found that the coefficient, by which the voltage between the direct-current brushes must be multiplied in order to get the effective voltage between successive rings is, for

2 rings	...	...	0·707
3 rings	...	...	0·612
4 rings	...	...	0·500
6 rings	...	...	0·354

In practice, there is a slight variation from these coefficients due to the fact that the air-gap flux is not sinusoidally distributed.

174. Derivation of the Equations for I_2 and I_3:—The power P delivered by the D.C. side$=EI$. The

intake of power is $E_2 I_2 \times$ power factor; but since the power factor is supposed to be unity, the intake of power is simply $E_2 I_2$ Therefore, ignoring losses of power, we have $E_2 I_2 = E I$.

But, $$E_2 = 0{\cdot}707 E,$$

$$E_2 I_2 = 0\ 707 E \times I_2 = EI.$$

Hence, $$0\ 707 I_2 = I,$$

or, in final form, the equation for I_2 is $I_2 = 1{\cdot}414 I$. Again, the direct-current output of power is EI, and the intake of power is $\sqrt{3} E_3 I_3$, the power factor being unity; that is, the power delivered by three-phase supply mains is equal to $\sqrt{3}$ times the voltage between mains multiplied by the current in each main. Therefore, ignoring power losses in the machine we have

$$\sqrt{3} E_3 I_3 = E I.$$

But, $E_3 = 0{\cdot}612 E$, (p. 308), so that $\sqrt{3} E_3 I_3$ or

$$\sqrt{3} \times 0{\cdot}612 \times E I_3 = EI.$$

Hence, $$\sqrt{3} \times 0{\cdot}612 I_3 = I,$$

or, in final form, the equation for I_3 is

$$I_3 = 0{\cdot}943 I.$$

175. Current Relations in Armature Coils:— Equate the alternating-current input to the direct-current output, and substitute the voltage ratios just found. Assume unity power factor and neglect the losses.

Let I = the direct current delivered through the brushes.

I_2 = the current in the armature coil in the single-phase circuits.

I_3 = the current in the armature coil in the three-phase circuits.

I_4 = the current in the armature coil for the quarter-phase circuits.

I_6 = the current in the armature coil for the six-phase circuits.

For single-phase converters

$$EI = 2 E_2 I_2 ; \qquad \therefore I_2 = 0{\cdot}707 I.$$

For three-phase converters

$$EI = 3 E_3 I_3 ; \qquad \therefore I_3 = 0{\cdot}544 I.$$

For quarter-phase converters

$EI = 4\ E_4 I_4$; $\therefore\ I_4 = 0{\cdot}500\ I.$

For six-phase converters—

$EI = 6\ E_6 I_6$ $\therefore\ I_6 = 0{\cdot}471\ I.$

Neglecting losses for the present, if E_n represents the pressure and I_n the effective alternating current in the armature coils between the successive slip-rings, then for the parts of the armature winding covered by each pair of poles

$$EI = nE_n I_n$$

$$= n\ \frac{E}{\sqrt{2}}\ I_n \sin \pi/n$$

Therefore, the maximum value of the alternating current is—

$$\sqrt{2}\ I_n = \frac{2\ I}{n \sin \pi/n}$$

Or, for a converter of n rings, the *current in the armature* circuits,

$$I_n = \frac{\sqrt{2}\ I}{n \sin \pi/n}$$

Since two circuits are connected to each collector ring, the currents in the mains are the vector differences of the currents in the circuits.

Let the subscript r indicate the currents at the rings, then the currents in the mains will be :—

For a—

two-ring converter (single-phase) $I_{2r} = 2\ I_2 = 1{\cdot}41\ I$;

three-ring converter (three-phase) $I_{3r} = \sqrt{3}\ I_3$
$= 0{\cdot}943\ I$;

four-ring converter (two-phase) $I_{4r} = \sqrt{2}\ I_4$
$= 0{\cdot}707\ I$;

six-ring converter (six-phase) $I_{6r} = I_6 = 0{\cdot}471\ I.$

The general expression for *current in the mains*, or collector rings, is—

$$I_{nr} = 2\ I_n \sin \pi/n = \frac{2\sqrt{2}\ I}{n}$$

Actual Current Ratio:—In specific cases where exactness is desired, the current can be determined most conveniently from the direct-current output, actual alternate current voltage, actual efficiency and power-factor using the following formula :—

Alternating current (per terminal)

$$= \frac{\text{kW.} \times 1000}{E_a \text{ eff.} \times Y \times \text{P. F.}} \text{ amps.}$$

where E_a is the alternate-current voltage. Values of Y are given as follows :—

Number of Phases.	Values of Y.
Single-phase	1·00
Two-phase	2·00
Three-phase	1·73
Six-phase	3·00

Example 2. A rotary converter delivers 1,000 amperes of direct current, the field excitation being adjusted so that the intake of alternating current may be a minimum.

(*a*) If this converter is a two-ring converter, it must be supplied with 1,414 amperes of alternating current from single-phase mains.

(*b*) If this converter is a three-ring converter, it must be supplied with three-phase currents from three-wire mains, with 943 amperes effective in each main.

(*c*) If this converter is a four-ring converter, it must be supplied with two-phase currents from four-wire supply mains, with 707 amperes effective in each main.

(*d*) If this converter is a six-ring converter, it must be supplied with six-phase currents from six-wire mains, with 471 amperes effective in each.

Example 3. At 100 per cent. efficiency and unity power factor, what would be the alternating current per

line wire and voltage between rings of a single-phase converter which was delivering 500 kW. direct-current power at 220 volts ?

Solution :—

$$I_d = \frac{500,000}{220} = 2,273 \text{ amperes.}$$

$$\begin{aligned} I_1 &= 1{\cdot}41\ I_d \\ &= 1{\cdot}41 \times 2,273 \\ &= 3,205 \text{ amperes.} \\ E_2 &= 0{\cdot}707 \times 220 \\ &= 155{\cdot}6 \text{ volts.} \end{aligned}$$

Example 4. If the converter in Example 3 is operated on 95 per cent. power factor at 90 per cent. efficiency, what would be the alternating current and voltage when delivering 500 kW. direct current at 220 volts ?

Solution :—

$$\begin{aligned} \text{Alternating-current power} &= E_1\ I_1 \cos\phi \\ &= 0{\cdot}95\ E_1\ I_1. \end{aligned}$$

$$\begin{aligned} \text{Direct-current power} = E_d\ I_d &= 500,000 \text{ watts} \\ &= 0{\cdot}90 \text{ of } 0{\cdot}95\ E_1 I_1. \end{aligned}$$

$$\begin{aligned} E_1 &= 0{\cdot}707\ E_d \\ &= 0{\cdot}707 \times 220 \\ &= 155{\cdot}6 \text{ volts.} \end{aligned}$$

Therefore, since

$$E_d I_d = 0{\cdot}90 \times 0{\cdot}95 \times 155{\cdot}6 \times I_1 = 500,000 \text{ watts}$$

$$\therefore I_1 = \frac{500,000}{0{\cdot}90 \times 0{\cdot}95 \times 155{\cdot}6} = 3,759 \text{ amperes.}$$

176. Heat Losses at Unity Power Factor :— Consider a two-pole n-ring converter, as depicted in Fig. 4·09. Let M be the conductor midway between the

slip-ring connections A and B, and K, the conductor at a distance α from M. For the conductors in the circuit between A and B the value of α varies from 0 to $\pm\pi/n$. The maximum value of the alternating current $\sqrt{2}I_n$ flows when conductor M passes under the centre of the field pole (unity power factor assumed). Hence, the instantaneous value for any other position of the armature is

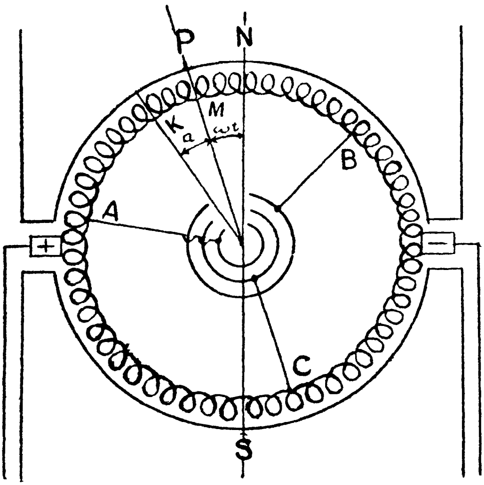


Fig. 4·09

$$i=\sqrt{2}\, I_n \cos \omega t - I/2.$$

When K reaches the positive brush $\alpha=\pi/2-\omega t$;

and at the negative brush $\alpha=-(\pi/2+\omega t)$ or $3\pi/2-\omega t$.

Also, $$I_n=\frac{\sqrt{2}\, I}{n \sin \pi/n} \quad \ldots \text{ (Art. 173)}$$

Therefore, $$i=\frac{2\, I \cos (\omega t)}{n \sin (\pi/n)}-I/2 \quad \ldots \quad (1)$$

Taking the line SN as the axis, the instantaneous current in any armature coil of an n-ring two-pole converter is, $i=\dfrac{2\, I \cos (\omega t \pm \alpha)}{n \sin \pi/2.} - I/2.$

The heat loss is proportional to the square of the current.

$$i^2 = \frac{4\,I^2\,cos^2\,(\omega t)}{n^2\,sin^2\,(\pi/n)} - \frac{2\,I^2\,cos\,(\omega t)}{n\,sin\,(\pi/n)} + I^2/4.$$

$$= (I^2/4)\left[\frac{16\,cos^2\,(\omega t)}{n^2\,sin^2\,(\pi/n)} - \frac{8\,cos\,(\omega t)}{n\,sin\,(\pi/n)} + 1\right] \quad \ldots\ (2)$$

The average heat loss is proportional to the average square of the current taken over a half-cycle from $-(\pi/2+a)$ to $+(\pi/2-a)$. Thus, average heat loss per conductor

$$= R\int_{-(\pi/2+a)}^{+(\pi/2-a)} i^2\,d\,(\omega t)/\pi \quad \ldots \quad \ldots\ (3)$$

in which R is the resistance of one armature conductor.

From equation (2) and (3) the heat loss

$$= R\int_{-(\pi/2+a)}^{+(\pi/2-a)} i^2\,d\,(\omega t)/\pi$$

$$= \frac{R\,I^2}{4\pi}\int_{-(\pi/2+a)}^{+(\pi/2-a)}\left[\frac{16\,cos^2\,(\omega t)}{n^2\,sin^2\,(\pi/n)} - \frac{8\,cos\,(\omega t)}{n\,sin\,(\pi/n)} + 1\right] d$$

$$= \frac{R\,I^2}{4\pi}\left[\frac{16}{n^2\,sin^2\,(\pi/n)}(\omega t/2 + \frac{sin\,2\,\omega t}{4}) - \frac{8\,sin\,\omega t}{n\,sin\,(\pi/n)} + \omega t\right]_{-(\pi/2+a)}^{+(\pi/2-a)}$$

$$= \frac{R\,I^2}{4\pi}\left[\frac{16}{n^2\,sin^2\,(\pi/n)}(\pi/4 - a/2 + sin\,2\,a/4)\right.$$

$$- \frac{8\,cos\,a}{n\,sin\,(\pi/n)} + \pi/2 - a - \frac{16}{n^2\,sin^2\,(\pi/n)}(-\pi/4 - a/2$$

$$+ \sin 2\,a/4) - \frac{8 \cos a}{n \sin (\pi/n)} + \pi/2 + a \Big]$$

$$= \frac{R I^2}{4\pi} \left[\frac{16}{n^2 \sin^2 (\pi/n)} (\pi/2) - \frac{16 \cos a}{n \sin (\pi/n)} + \pi \right]$$

$$= \frac{R I^2}{4} \left[1 - \frac{16 \cos a}{\pi n \sin (\pi/n)} + \frac{8}{n^2 \sin^2 (\pi/n)} \right] \quad \ldots \quad (4)$$

177. To find the average heating around the whole periphery, *i.e.*, average heat in the armature, the average value for any conductor of a phase as given in eqn. (4) must be integrated for all possible values of a between the limits $a = -\pi/n$ and $a = +\pi/n$, and the result divided by the angular width of the phase, $2\pi/n$.

Thus, average heat in armature

$$= \frac{R I^2}{4 \cdot \frac{2\pi}{n}} \int_{-\pi/n}^{+\pi/n} \left[1 - \frac{16 \cos a}{n \pi \sin (\pi/n)} + \frac{8}{n^2 \sin^2 (\pi/n)} \right] d\,a$$

$$= \frac{R I^2}{4 \cdot \frac{2\pi}{n}} \left[a - \frac{16 \sin a}{n \pi \sin (\pi/n)} + \frac{8\,a}{n^2 \sin^2 (\pi/n)} \right]_{-\pi/n}^{+\pi/n}$$

$$= (R I^2/4) \left[1 - \frac{16}{\pi^2} + \frac{8}{n^2 \sin^2 (\pi/n)} \right] \quad \ldots \quad (5)$$

One-half of the armature is taken into the calculation, both for the alternating current and the direct current, and, therefore, the ratio is the same as for the whole armature. The average armature heating is, therefore, $\left[1 - \frac{16}{\pi^2} + \frac{8}{n^2 \sin^2 (\pi/n)} \right]$ times that of the same machine used as a direct-current generator of the same

output. In other words, the ratio

$$\frac{\text{Heating of rotary armature}}{\text{Heating of D. C. generator armature}}$$

$$=1-16/\pi^2+\frac{8}{n^2\sin^2(\pi/n)}, \quad \ldots \quad (6)$$

at the same current ouput.

Hence, for the same temperature rise, an n-ring rotary converter transmits

$$\frac{1}{\sqrt{1-16/\pi^2+\dfrac{8}{n^2\sin^2(\pi/n)}}} \quad \ldots \quad (7)$$

times as much current as when the machine operates as a direct-current generator.

From expressions (6) and (7), the heating of armature and the power rating (by mean armature heating) of the synchronous converter are respectively found in terms of the direct-current generator, as shown in the following table:—

1	2	3	4	5	6	7
As a direct-current generator.	As a single-phase converter $n=2$.	As a three-phase converter $n=3$	As a two-phase converter $n=4$.	As a six-phase converter $n=6$.	As a twelve-phase converter $n=12$.	∞—phase.
Heating : 1·00	1·37	0·555	0·37	0·26	0·20	0·187
Rating : 1·00	0.85	1·34	1·64	1·96	2·24	2·31

178. Current Relations and Heat Losses for Power Factor less than Unity.—In the discussion

of the current relations and heat losses in the preceding article, two assumptions were made :—

First, that the field excitation was adjusted for *unity* power factor ; and secondly, that *no energy was lost in the converter*. If m per cent. of the alternating current is used in causing rotation, and the current lags or leads by an angle ϕ, the expression for the current, I_n, becomes

$$I_n = \frac{\sqrt{2}\, I}{(1-m)\, n \sin(\pi/n) \cos\phi}$$

Similarly, the maximum value of the alternating current is displaced by an angle ϕ from the voltage wave. Hence, the instantaneous current flowing in the armature conductor is changed from the expression in equation (1), Art. 176. to the value.

$$i = \frac{2\, I \cos(\omega t \pm \phi)}{(1-m)\, n \sin(\pi/n) \cos\phi} - I/2 \qquad \ldots (1)$$

The positive sign is taken for leading currents and the negative for lagging currents.

As in the previous case, the average heating per conductor

$$= R \int_{-(\pi/2+a)}^{+(\pi/2-a)} i^2\, d(\omega t)/\pi$$

$$= \frac{R I^2}{4\pi} \int_{-(\pi/2+a)}^{+(\pi/2-a)} \left[\frac{16 \cos^2(\omega t \pm \phi)}{(1-m)^2 n^2 \sin^2(\pi/n) \cos^2\phi} - \frac{8 \cos(\omega t + \phi)}{(1-m)\, n \sin(\pi/n) \cos\phi} + 1 \right] d(\omega t)$$

$$\frac{R I^2}{4\pi} \left[\frac{16}{(1-m)^2 n^2 \sin^2(\pi/n) \cos^2\phi} (\omega t/2 + \sin 2(\omega t \pm \phi)/4) - \frac{8 \sin(\omega t \pm \phi)}{(1-m)\, n \sin(\pi/n) \cos\phi} + \omega t \right]_{-(\pi/2+a)}^{+(\pi/2-a)}$$

$$=\frac{R\,I^2}{4\pi}\left[\frac{16}{(1-m)^2\,n^2\,sin^2\,(\pi/n)\,cos^2\,\phi}\left(\pi/4-a/2\right.\right.$$

$$\left.+\frac{sin\,(2a\pm\phi)}{4}\right)-\frac{8\,cos\,(a\pm\phi)}{(1-m)\,n\,sin\,(\pi/n)\,cos\,\phi}$$

$$+\pi/2-a-\frac{16}{(1-m)^2\,n^2\,sin^2\,(\pi/n)\,cos^2\,\phi}\left(-\pi/4\right.$$

$$\left.-a/2+\frac{sin\,(2\,a\pm\phi)}{4}\right)-\frac{8\,cos\,(a\pm\phi)}{(1-m)\,n\,sin\,(\pi/n)\,cos\,\phi}$$

$$\left.+\pi/2+a\right]$$

$$=\frac{R\,I^2}{4\pi}\left[\frac{16}{(1-m)^2\,n^2\,sin^2\,(\pi/n)\,cos^2\,\phi}(\pi/2)\right.$$

$$\left.-\frac{16\,cos\,(a\pm\phi)}{(1-m)\,n\,sin\,(\pi/n)\,cos\,\phi}+\pi\right]$$

$$=(R\,I^2/4)\left[1-\frac{16\,cos\,(a\pm\phi)}{\pi(1-m)\,n\,sin\,(\pi/n)\,cos\,\phi}\right.$$

$$\left.+\frac{8}{(1-m)^2\,n^2\,sin^2\,(\pi/n)\,cos^2\,\phi}\right]\quad\ldots\quad(2)$$

The quantity within brackets gives the ratio of heating of an armature conductor to that of a direct-current generator of the same output.

179. To find the average armature heating, it is simply necessary to integrate the expression (2), as in the previous case, between the limits of a phase, or between $-\pi/n$ and $+\pi/n$, and divide the result by $2\,\pi/n$. Thus, average heating of armature

$$=\frac{R\,I^2}{4.\frac{2\,\pi}{n}}\int_{-\pi/n}^{+\pi/n}\left(1-\frac{16\,cos\,(a\pm\phi)}{\pi\,(1-m)\,n\,sin\,(\pi/n)\,cos\,\phi}\right.$$

$$\left.+\frac{8}{(1-m)^2\,n^2\,sin^2\,(\pi/n)\,cos^2\phi}\right)da$$

$$=\frac{R\,I^2}{4.\,\frac{2\,\pi}{n}}\Big[a-\frac{16\,sin\,(a\pm\phi)}{\pi\,(1-m)\,\;n\;\,sin\,(\pi/n)\,cos\;\,\phi}$$

$$+\frac{8\;a}{(1-m)^2\;n^2\;sin^2\;(\pi/n)\;cos^2\;\phi}\Big]_{-\pi/n}^{+\pi/n}$$

$$=\frac{R\,I^2}{4.\,\frac{2\,\pi}{n}}\Big[\frac{2\,\pi}{n}-16\frac{sin\,(\pi/n\pm\phi)+sin\,(\pi/n\mp\phi}{\pi\,(1-m)\;\,n\;\,sin\;\,(\pi/n)\;\,cos\,\phi}$$

$$+\frac{16\;\pi/n}{(1-m)^2\;n^2\;\;sin^2\,(\pi/n)\;\;cos^2\;\,\phi}\Big]$$

$$=\frac{RI^2}{4}\Big(1-\;\frac{16\;sin\;\pi/n\;cos\;\phi}{\pi^2\;(1-m)\;sin\;\;(\pi/n)\;cos\;\phi}$$

$$+\frac{8}{(1-m^2)\;n^2\;sin^2\;\;(\pi/n)\;cos^2\;\phi}\Big)$$

$$=\frac{RI^2}{4}\left(1-\;\frac{16}{\pi^2(1-m)}+\frac{8}{(1-m)^2n^2sin^2(\pi/n)\;cos^2\phi}\right)\;(3)$$

The expression within brackets is evidently the ratio of the average heating of the rotary converter to that of the same machine used as a direct-current generator of the same output.

The conditions for maximum and minimum heating of a coil are obtained from the expression within parenthesis of equation 2. Thus, maximum heating occurs when $cos\;(a\pm\phi)$ is a minimum, *i.e.*, when $a=\pi/n$ and minimum heating occurs when $cos\;(a\pm\phi)$ is a maximum, *i.e.*, when $a=\pm\phi$, according as the current leads or lags.

180. The Variation of Current and Heating in Rotary Converter:—Since the machine is acting both as a motor and a generator, there are superimposed two currents in any conductor, and these currents are

flowing in opposite directions ; and as such the net current flowing in it is the difference between the two currents.

Take a particular coil, the direct current is constant in amount and direction while the armature rotates through one pole pitch, and conversely during rotation through the next pole pitch. In any coil midway between the A. C. taps the alternating current is a maximum when this coil is half-way between the brushes, and the current falls to zero as the coil reaches the interpolar position, and the D. C. is reversed at the same instant with A C The result is that the current will have a wave shape and frequency somewhat as shown in Fig. 4'10.

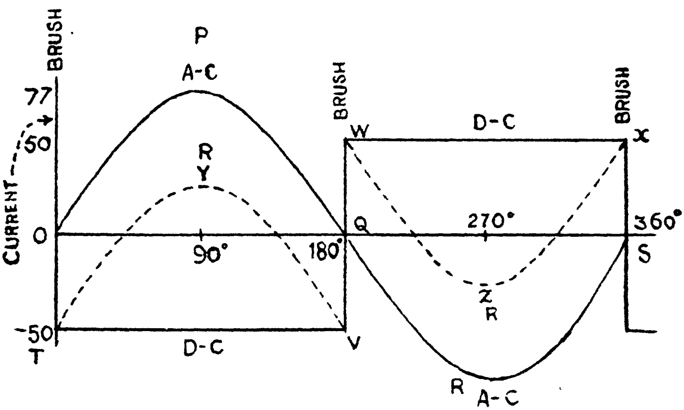


Fig. 4'10

A coil very near one of the A.C. taps will carry a D. C., as just stated, but the A. C. in the coil is the same as that in the middle coil and has its maximum when the middle coil, and not this particular coil, is at the middle of the poles The A. C. in this coil, Fig. 4'11, may reach its maximum value soon after the coil has passed a brush.

In any coil on either direction from the centre the A. C. is the same, but the instant of reversal of D. C. becomes either sooner or later than that of A. C. The

further a coil situated from the middle coil of a group,

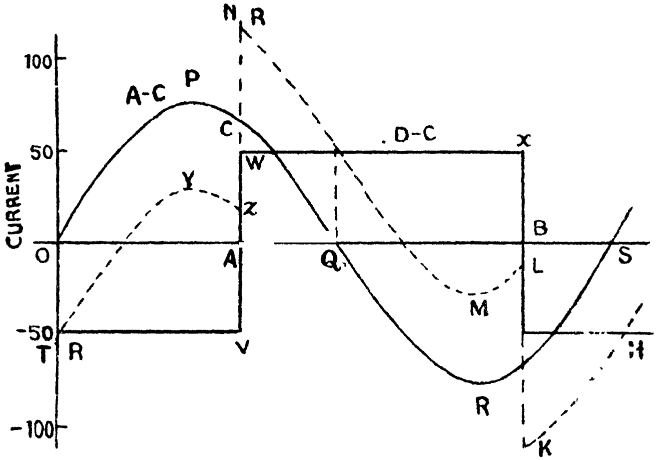


Fig. 4·11.

the greater is the phase displacement of its alternating current, the greater is the value of the resultant current and the greater is the heat effect. Thus, although the heating effect in a rotary converter winding is less than that of a D. C. machine, the heating is different in each and every coil, is minimum in the central coil with unity power factor, and is maximum at the coil nearest the taps; and the greater the angle between taps, the greater is the total heating effect, and there is lesser distortion of magnetic field due to armature reaction. Hence, the commutation is fixed and we may get sparkless running with fixed brushes through a wide range of load due to a nearly constant and uniform field. The operation is much better than a D. C. generator. Hence, much more power can be got out of a given size machine run as a rotary. Cheapness, increased efficiency and gain in floor space are added advantages.

181. Converter Ratings :—

If $K'W'$=the rating as a synchronous converter,
$K\ W$=the rating as a direct-current generator,
we have from expression 7, p. 319,

$$K'W' = K\ W\ \frac{1}{\sqrt{8/(n^2\ sin^2\ \pi/n) - 16/\pi^2 + 1.}}$$

Note.—From equation 2, p 321, we have a corresponding ratio for the heating of a conductor or coil, *viz*

$$\frac{\text{Heating of rotary coil}}{\text{Heating of D. C. generator coil}}$$

$$= 1 - \frac{16\ cos\ a}{\pi n\ sin\ (\pi/n)} + \frac{8}{n^2\ sin^2\ (\pi/n)}.$$

This ratio is a maximum for that coil of the phase for which $a = \pi/n$, that is, for the largest possible value of a, and is $\left[1 - \frac{16\ cos\ (\pi/n)}{\pi\ n\ sin\ (\pi/n)} + \frac{8}{n^2\ sin^2\ (\pi/n)}\right]$; the ratio is a minimum for $a=0$, and is $\left[1 - \frac{16}{\pi\ n\ sin\ (\pi/n)}\right.$ $\left. + \frac{8}{\pi^2\ sin^2\ (\pi/n)}\right]$.

182. Advantages to be Gained by Increasing the Number of Phases and Slip-Rings on a Rotary Converter :—

The loss in the armature is decreased by increasing the number of slip-rings, since the A. C. is more uniformly distributed through the windings and the output increased

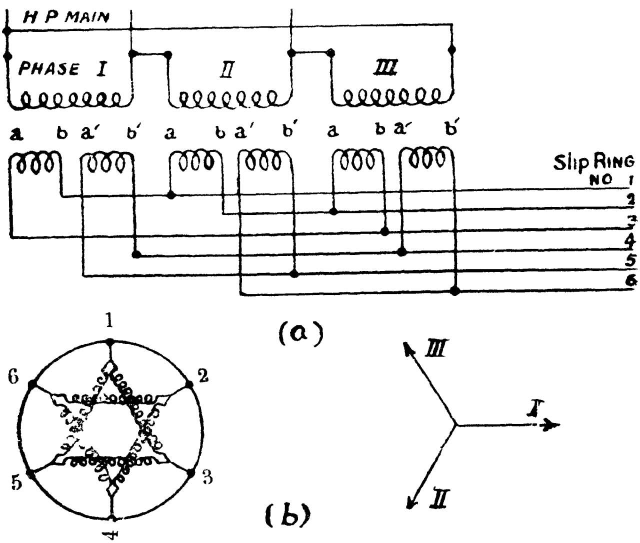
A six-phase machine has nearly double the output of the similar size D. C. armature with the same armature losses. Another result of this is the better balancing of the D. C. and A. C. magnetic action in the armature, resulting in commutation free from sparking and flashing.

The greater the number of slip-rings, the less is the tendency of the machine to hunt than if supplied with fewer phases.

It will be noticed that with single-phase supply the rotary converter is inferior to the D. C. generator, but all polyphase rotaries are superior in permissible output, and will carry a greater output without falling out of step.

183. Supply of Six-Phase Rotaries:—Six-phase rotaries have advantage over three-phase ones as regards output and the consequent higher efficiency. But three-phase high-tension supply is the usual practice from the point of view of economic consideration and ease of operation. However, a three-phase H. T. supply can be very conveniently transformed into six-phase for connecting to the armature leads by means of step-down transformers.

There are three methods in use for providing current to the leads. These are :—(*a*) double-delta, (*b*) diametral, and (*c*) hexagonal or ring.



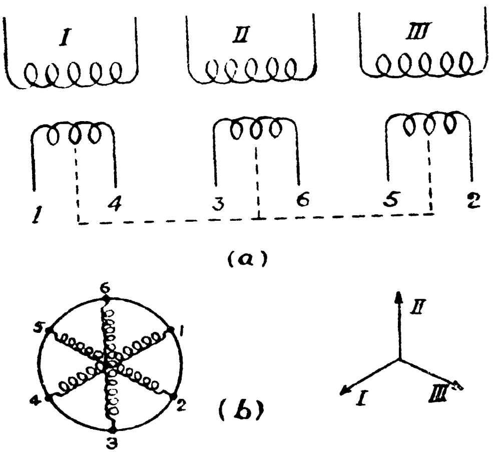
Double-Delta Supply to Six-Phase Rotaries.

Fig. 4·12

(*a*) In the *double-delta*, Fig. 4·12, method of connection the primaries are connected either Y or Δ.

Each has two secondaries containing equal number of turns of the same section (see Fig. 4·12 *a*). Three of these, one from each phase, are connected together in delta and leads taken from this delta to three of the alternate tapping points 1, 3, and 5. The other set of three windings are also connected in delta but with reversed connections, *e.g.*, Ia' to IIb' compared with Ib to IIa. They thus produce P. Ds. suitable for connection to the alternate tapping points 2, 4, and 6 previously omitted.

Fig. 4·12 *b* shows the armature winding of the rotary as a circle and the tapping points as numbered dots on this circle. Any two secondaries belonging to the same phase are connected across two pairs of tapping points (*e.g.*, 5-1, and 4-2 for phase *I*) between which the P. Ds. are equal in magnitude and of the same phase.



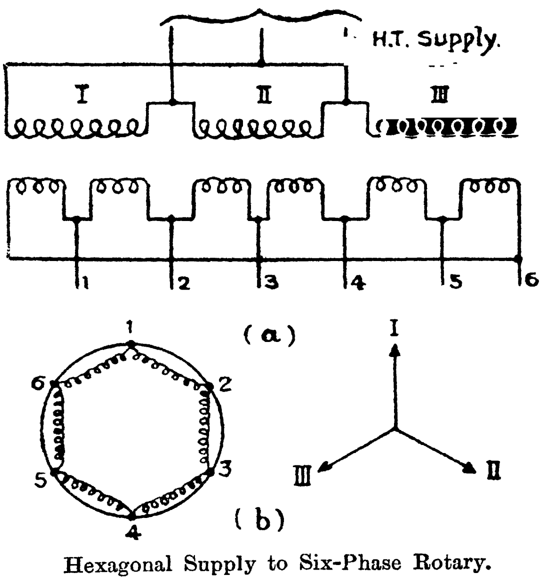
Diametral Supply to Six-Phase Rotary.
Fig. 4·13

(*b*) In the diametral method, Fig. 4·13, each transformer has got only one secondary, the ends of each of these being

connected to tapping points 180° electrical apart. The method of connections is shown in Fig. 4·13 (*a*) and (*b*).

The centre points of the three secondaries are at the same potential, *viz.*, midway between the positive and negative D. C. mains. If tappings are taken from these points and joined to form a star point, the connections become double-*Y*.

(*c*) In the hexagonal (or ring) method two equal secondaries per phase are required as for the double-delta, but their voltages are lower and currents correspondingly greater (see Ex. 5, p. 329). The connections are shown in Fig. 4·14 (*a*) and (*b*). The secondaries of phase *1* are connected across slip-rings 2-3 and 6-5, respectively, and similarly for those of the other two phases. It will be seen that the six secondaries form a closed mesh.



Hexagonal Supply to Six-Phase Rotary.

Fig. 4·14

Example 5. A six-phase rotary is to supply 500 amperes at 450 volts from three-phase mains at 6,600 line volts. If the delta-connected primary windings of the transformers have each 1,000 turns, find the number of turns and currents in the secondary windings for each of the three methods of connections :—(*a*) Double-delta, (*b*) Diametral or double-Y, and (*c*) Hexagonal, neglecting all losses.

Solution :—

(*a*) Double-delta :—

The P. D. across each secondary $= 0{\cdot}612 \times 450$ volts
$= 275$ volts.

Just as for three-phase rotary.

Number of turns in each secondary $= 1{,}000 \times 275/6{,}600$
$= 42$ turns,

Current in each lead $= 0{\cdot}471 \times 500 = 235{\cdot}5$ amperes.

$\therefore$ Current in each secondary $= 235{\cdot}5/\sqrt{3} = 136$ amperes, which is half the current for a three-phase rotary of the same output with delta-connected secondaries.

(*b*) Diametral or Double-Y :—

P. D. across each complete secondary $= 0{\cdot}707 \times 450$
$= 318$ volts.

Just for a monophase rotary.

$\therefore$ Number of turns in each secondary $= 1{,}000 \times 318/6{,}600$
$= 48$ turns.

For double-Y of this, *viz.*, 24 turns from each secondary current in each lead $= 0{\cdot}471 \times 500 = 235{\cdot}5$ amperes.

$\therefore$ Current in each secondary $= 235{\cdot}5$ amperes.

This is one-third of the current for a monophase rotary of the same output.

(*c*) Hexagonal :—

P. D. across the secondary $= 0{\cdot}354 \times 450$ volts.
$= 159$ volts.

$\therefore$ Number of turns in each secondary $= 1{,}000 \times 159/6{,}600$
$= 24$ turns.

Current in each lead $= 235{\cdot}5$ amperes.

Current in each secondary $= 235{\cdot}5$ amperes.

Since the current in the lead is the vector difference of two equal secondary currents with 60° phase difference, full-load secondary ampere-turns per phase

(*a*) $= 2 \times 42 \times 136 = 11{,}424$
(*b*) $= 48 \times 235{\cdot}5 = 11{,}304$
(*c*) $= 2 \times 24 \times 235{\cdot}5 = 11{,}304$

i.e., practically the same in all cases. Hence, we find that the same amount of copper is required for all methods except for the effect of the greater total amount if insulation required for the larger number of turns in the double-delta.

Example 6. A six-ring converter diametrally connected to three single-phase transformers at full load delivers 1,000 kW. at 500 volts direct current. The converter has a full-load efficiency of 93 per cent. at unity power factor. The line voltage is 11,000.

(*a*) What must be the full-load secondary voltage of each transformer ?
(*b*) What must be the voltage ratio of each transformer if the primaries are delta-connected to the line ?
(*c*) What current will each transformer terminal deliver under these conditions ?

Solution :—(*a*) The secondary voltage of the transformers must equal the effective value of the diametral induced alternating E. M. F.

$$E = 0{\cdot}71 \times 500 = 355 \text{ volts.}$$

(*b*) The voltage ratio of each transformer must be

$$\frac{11{,}000}{355} = 31.$$

(*c*) At unity power factor, each transformer must deliver

$$\frac{1}{3} \text{ of } \left(\frac{1{,}000}{0{\cdot}93}\right) \text{ kW.} = 358 \text{ kW.}$$

∴ At unity power factor each transformer must deliver

$$\frac{358{,}000}{355} = 1{,}009 \text{ amperes}$$

Example 7. A six-ring converter, connected double-delta to three single-phase transformers, at full load delivers 1,000 kW. at 500 volts. The converter has a full-load efficiency of 93 per cent. while operating at unity power factor. The line voltage is 11,000 volts.

(*a*) What is the full-load secondary voltage of each transformer ?

(*b*) The primaries are delta-connected to the line. What is the voltage ratio of each transformer ?

(*c*) What current does each transformer coil deliver under these conditions ?

Solution :—(*a*) The voltage across a single coil of each transformer is 0·62 of the voltage between the direct-current brushes.

Voltage of one coil of transformer $=0{\cdot}62\times500$
$=310$ volts.

If the two coils of each secondary were joined in series, the secondary voltage would be $2\times310=620$ volts.

(*b*) The voltage ratio of each transformer with the two secondaries in series is

$$\frac{11{,}000}{620}=17{\cdot}7$$

(*c*) Input at unity power factor and 93 per cent. efficiency equals $1{,}000/0{\cdot}93=1{,}075$ kW.

Each coil delivers 1/6 of 1,075 kW. $=179{\cdot}2$ kW.

Each coil must deliver $179{,}200/310=578$ amperes.

184. Relative Efficiency :—The efficiency of a converter is about 93 per cent., of a transformer 97 per cent.; thus the efficiency of the combination is about 90 per cent. The efficiency of a synchronous motor is about 93 per cent. and of a D. C. generator 92 per cent. Thus the combination has an efficiency of 85·5 per cent. If the supply voltage is greater than 13,000 volts, transformers will also be needed for the motor generator set and the net efficiency would then be 83 per cent.

185. Effect of Power Factor on Armature Heating :—The effective current in the armature conductors of a rotary converter is the difference between the

alternating current delivered to the windings and the D. C. The average copper loss in a rotary converter armature, when run *at* 100 % *power factor*, is considerably less than when it would be in the same machine run as D. C. generator (being approximately 59 % of this loss for a three-phase, and 27 % for a six-phase armature). Moreover, this loss is not uniformly distributed among the armature conductors as it is in a D. C generator, but is much greater in the conductors between taps. Thus at 100 % power factor the maximum loss in any one conductor is 125 % of the uniform loss in the corresponding D. C. generator for a three-phase converter and 43 % for a six-phase converter. This big difference in maximum loss between the three-phase and six-phase windings explains the use of six-phase windings in practically all converters.

These percentages are true only at 100 % power factor. They increase rapidly as the power factor is varied from 100 %. Thus at 98·5 % power factor the maximum loss is 27 % greater than at 100 % power factor in a three-phase converter, and more than 40 % in a six-phase converter. For this reason rotary converters should operate with a power factor as near 100 % as possible. Each machine is designed to carry, without excessive heating, the wattless current required to give the specified D. C. voltage variation, but if this variation is exceeded or the A. C. supply voltage differs from the normal value, care should be taken that the resulting wattless current will not cause dangerous heating.

When temperature tests are made after installation to determine the operating temperatures under the guaranteed conditions, care should be taken that the D. C. and A. C. supply voltages are within the specified limits. Failure to observe this point will make the tests of no value as a check against the guaranteed figures, since the losses vary much with variation in the power factor.

186. Voltage Variation (*vide* Article **172**):—With reactance in the supply circuit of the converter, the voltage of the slip-rings may be varied through a small range by changing the power factor of the supply current. The power factor may be varied by varying the excitation

of the main field windings. The D. C. voltage is varied in the compound wound converter by the action of the series windings and reactance, the two combining to vary the A. C. voltage. While the arrangement of field windings is the same as in the compound wound D. C. generator, the theory and action are entirely different. With lagging wattless currents the reactance voltage subtracts from the line voltage and with leading wattless currents it adds to the line voltage. At unity P. F. the effect of the reactance voltage is practically negligible. Lagging wattless currents are obtained by making the field excitation less than normal, and leading wattless currents by making the field excitation more than normal.

187. Effect of Series Field on Fluctuating Loads :—When converters carry widely and rapidly fluctuating loads, the series field should be relatively weak so as to avoid sudden wide variations in voltage and wattless current with sudden changes in load. A drooping voltage at the overloads is also desirable to assist in reducing the current under the extreme load conditions. A compound-wound rotary converter, in its voltage characteristic, is more stable in operation on rapidly varying loads and when the circuit-breaker of the machine opens on very heavy currents.

188. Starting of Rotary Converters :—Before starting any converter the following routine should be regularly observed :—

(1)The alternating-current and direct-current brushes should be examined to see that they move freely in their holders.

(2) Examine the bearing housings to make sure that there is plenty of oil in the wells, and that the rings are free to turn.

(3) See that the speed-limit device is in operating condition

(4) Open all the knife switches on the switchboard, on the starting panel, and pedestals (if used), and on the converter frame for both the alternating and direct-current circuits. The shunt-field switch on the switchboard is to remain closed in the operating position with the field

resistance about half in for alternating-current starting and all out for direct-current starting. When the machine has been placed on the line, examine the oil-rings to see that they are properly seated on collector or commutator and are not sparking.

Phasing Out :—Before starting any converter for the first time, if it is necessary to predetermine the direction of rotation, it will be necessary to test the wiring to ensure that the connection of the incoming line phases to the machine phases, is in proper sequence With each start by induction starting motor or from the D C. side some method for indicating synchronism between machine and line is necessary. The elementary principle of the method of determining synchronism, when two alternating-current machines are of the same frequency and are in phase, is illustrated in the second volume.

Method of Starting :—There are four methods in common use for starting rotary converters, namely, (*a*) from alternating-current side by tap-starting method ; (*b*) from the alternating-current side, as an induction motor ; (*c*) from the direct-current side, as a shunt motor ; and (*d*) by means of a special direct-connected starting motor, usually of the squirrel-cage induction type.

(a) Tap-Starting :—This is a very commonly used method, that no synchronising gear is required in this method, but a moving coil zero-centre voltmeter is connected across the brushes on the D. C. side, and the field winding is split in a number of sections by means of a "field break-up switch." On the A C. side either auto-transformers are interposed between the slip-rings and the main transformer, or the secondaries of the main transformer are used as auto-transformers. When starting, the D. C switch and the field break-up switch are opened, and the brushes lifted off the commutator; the A. C. switch is closed, the auto-transformer being arranged so that the smallest voltage is appled to the brushes. An alternating current flows through the armature and produces a rotating magnetic field, the lines of force of which sweep past the dampers on the pole-faces, thereby inducing currents in them. Hence, the armature starts up

like an inverted squirrel-cage induction motor. Now, the rotating field produced by the armature rotates at synchronous speed relative to the armature, and therefore, as the speed of the armature increases, the actual speed in space of the rotating field becomes smaller and smaller, until eventually its poles move so slowly past the salient poles of the field system, that they magnetise the latter.

The two systems of poles then grip each other, the rotating field, therefore, becoming stationary in space. This means that the armature must now be running at synchronous speed, the rotary having what is called "jumped into step." It is obvious that it is possible for the polarity of the D C. side to come up in the wrong direction, because this polarity depends upon the ultimate polarity of the main poles, and, therefore, on the relative positions of the main poles, and the rotating field at the instant the converter jumps into step If the polarity on the D. C. side is wrong, it will be indicated by the zero-centre voltmeter being deflected in the wrong direction. It can be corrected by what is called "slipping a pole." The field switch is momentarily reversed, thus causing the armature field to be repelled by the main field, and as a result each pole of the armature field moves on towards the next main pole. This is indicated by the needle of the zero-centre voltmeter swinging over the right side, the field break-up switch being closed in the right position. Finally, the converter is connected to the D.C. system by closing the D. C. switch.

The field is split up into section by the field break-up switch, because at the moment of starting, the actual velocity in space of the armature field is the synchronous speed, and, consequently, owing to the very large number of turns, a very high voltage would be induced in the field winding When the armature is running at synchronous speed, the armature field is stationary in space, and, consequently, no voltage is induced in the field winding, the sections of which can, therefore, be all connected in series. For the same reason the brush gear on the D. C. side is lifted at starting, otherwise heavy currents would circulate across the brush faces and cause excessive sparking.

The full A. C. voltage is not applied to the slip-rings at starting, because of the very heavy rush of current which would be very nearly wattless, so that it would probably interfere with the voltage regulation of the line.

Procedure :—

(1) Close the oil circuit-breaker on the high-tension side of the transformer.

(2) Lift the D. C. brushes from the commutator if brush-lifting gear is fitted.

(3) Close the double-throw starting switch to the starting position. If the armature revolves in the wrong direction, shut down and change the alternating current cable connections on either the H.T. or L.T. side. If the connections are two-phase, interchange the two leads of either one of the phases; if three-phase, interchange any two leads; if six-phase, interchange two pairs of leads and proceed as before. The rotary converter should come up to synchronous speed in from 30 to 60 seconds and lock into step, indicating this condition by a steady current on the A.C. side of the converter and a continuous deflection on the D.C. voltmeter.

(4) If the D. C. voltmeter indicates a reversed polarity, throw the field switch to the reverse position, thus reversing the shunt field and connecting it directly across the armature. The voltmeter pointer will swing back towards zero. When it reaches zero, throw the field switch to the operating position. If the voltage now comes up with the right polarity, proceed as directed in No. (5). If, however, the converter fails to reverse, and the voltage again comes up with the right polarity, the starting switch should then be closed again in the starting position, repeating these operations until correct polarity is obtained.

(5) When the machine is up to synchronous speed, and the D.C. voltmeter shows correct polarity, throw the starting switch to the running position, pausing momentarily on the buffer resistance contacts, as this will reduce the rush of current. When brush-lifting gear is provided on the D.C. side, no buffer resistances are required. The

amount of current taken from the line when throwing to full voltage can be made a minimum by slightly over-exciting the field on the basis of normal voltage.

(6) Lower the D.C. brushes to the commutator.

Note :—Do not open the main H.T. switch with the rotary running on the starting taps, as the speed of the machine may be sufficient to cause the rotary to run up to a voltage considerably higher than that corresponding to the starting taps and so cause an excessively high voltage on the primary of the transformer.

(7) (*a*) For two-wire service :—

Close the D.C. circuit-breakers. Then close equaliser and (if this is on the negative side) the negative main switch ; if on the positive, the positive main switch. Adjust shunt-field current to give correct voltage for paralleling. Close the other main switch.

(7) (*b*) For three-wire service :—

Close the D.C. circuit-breakers, negative equaliser and negative main switch. Adjust shunt-field current to give correct voltage for paralleling. Close the positive equaliser, positive main switch and neutral switch.

(8) Adjust shunt field to correct setting for desired D. C. voltage.

(**b**) **As an Induction Motor** :—In this method polyphase currents at a suitable voltage are supplied to the collector rings. The resulting torque, developed by the armature, will bring the converter up to synchronous speed in from one to two minutes. Usually, low-voltage taps on the main transformers are used to give a lower starting voltage. This method of starting has the advantage of making synchronising unnecessary, but, on the other hand, it requires a large starting current, which, if the converter is relatively large, as compared with the alternator supplying it, causes an excessive drop of voltage throughout the circuit.

A difficulty sometimes met in this method of starting is, that the converter can drop into synchronism at either polarity. But its polarity can be reversed by strongly exciting the field in the right direction by some

outside source, as another converter, etc , or by momentarily opening the circuit and thereby letting the converter slip one pole. When several rotary converters are to supply direct current to common busbars, special care must be taken to see that the polarity of a given machine is correct before it is connected to busbars If the machine happens to come up to the speed with the wrong polarity, the field " break-up " switch must be thrown from one position to the other, thus reversing the field. Obviously, while starting, the direct-current side of the converter must be open-circuited to prevent the circulation of a large induced alternating current in both the shunt and the series field-winding, for the E. M. F. between the commutator brushes is alternating until synchronism is reached The induced current would not only cause excessive heating, but would also hinder starting by its breaking effect.

Procedure :--

(1) H. T. or L. T. Synchronising.

(1) If L. T. synchronising, close the oil circuit-breaker on the H. T. side of the transformers.

(2) Insert the voltmeter plug of the D C. voltmeter. Insert the synchronising plug, causing the synchronising lamps to burn dimly.

(3) Start the converter by closing the switch which controls the starting motor. In case the machine rotates in the wrong direction, reverse starting motor leads as described for rotary converter under "Alternating Current Self-Starting."

(4) Build up the D. C. voltage to approximately the line voltage by adjusting the field rheostat.

(5) In some cases in order to get synchronous speed, it is necessary to insert a small resistance in one phase of the starting motor circuit.

(6) Phase out machine as described before.

(7) When the lamps or synchroscope indicates synchronism, close the A. C. switches connecting the machine to the line.

(8) Open the switches controlling the starting motor and the synchronising resistance.

(9) Proceed as with alternate-current tap-starting (7*a* and *b*).

(2) Self-synchronising modification of the method (*d*) is sometimes employed, in which the converter is started from rest by means of a separate starting motor and then thrown directly on to the alternating current buses. This method combines advantages of separate motor starting and self-starting from the alternating-current side, in that it obviates the necessity of synchronising and insures the rotary cominig in with the right polarity ; on the other hand, it requres somewhat more time than the self-starting method and a heavier line current than with the induction-starting motor alone.

Messrs. Siemen's self-synchronising rotary converters have the stator windings of the pony motor in series with the A. C. side of the rotary. The synchronism is improved by placing a non-inductive resistance in parallel with the pony motor. By this method the current in the armature of the converter is brought to phase with the voltage thereby increasing the synchronising torque, the fields circuit is kept open until the synchronising speed has been reached.

Procedure :—

(1) Close the H. T. oil switch and the shunt-field switch

(2) Close the three-pole starting switch in the top position, thus connecting the windings of the starting motor direct across the transformer.

(3) When approximately normal speed is reached and the D. C voltage has built up to above half normal value, the starting switch is thrown over to the bottom position, so connecting the starting motor winding in series with the rotary armature windings, when the rotary will quickly pull into synchronism.

(4) The D. C. voltage fluctuates until the rotary is in step, when the voltage rises to a steady value. Adjust the field rheostat to give minimum voltage across the starting motor (this condition will correspond to a definite D. C voltage, which can be found by trial). The main A. C. switch is then closed, short-circuiting the starting

motor stator. The converter being in synchronism before the switch is closed and being excited to correct voltage, the closing of the switch causes neither a heavy rush of current nor injurious sparking at the commutator.

(5) Proceed as with alternating-current tap-starting.

By leaving the starting switch in the first position the machine can be run at full speed, or slightly above the normal speed, unexcited for commutator grinding, but the slip-ring brushes should be raised from the rings.

Note :—If due to any abnormal conditions the residual magnetism should have become reversed, so giving the wrong polarity, it can be corrected as follows :—

Start the machine with the starting switch in the bottom position, the field switch open and the rheostat set to give a strong field. As the machine approaches synchronous speed, the D. C. voltage will swing slowly to both sides of zero and the field switch should be closed when the voltage has the correct polarity.

(c) As a Shunt Motor :—When a direct-current supply is available, as from a storage battery, or direct-current generator, or another converter already in operation, the converter may be started as a direct-current shunt machine, the alternating-current main switch being open. The method is convenient and is used in many installations.

In this method of starting, the fields should be fully excited *by closing the field switch first* and there should be *a resistance in series with the armature when the motor switch is closed.* Failure to excite the field may cause the converter to increase its speed to a dangerous extent, just as in the case of direct-current shunt motor with excessively weak field ; for, in starting the converter from the direct-current side it is not running as a synchronous motor but as a simple shunt direct-current motor. If the converter is compound-wound, *the series-field current must be opened*, otherwise the current flowing through it will magnetise the field poles in opposition to the shunt-field windings (differential compounding) and may even prevent the machine from starting.

When normal speed is reached, the starting rheostat is cut out, and the field strength varied until the synchronising device* shows that the converter is in synchronism with the generator; then the main alternating current switch is closed.

When a rotary converter is started as a direct-current motor, it is easy to bring the machine into operation with a particular direct-current brush or set of brushes positive.

Procedure :—

(1) See that all switches are open, and if there is a series-field, that it is out of circuit if a switch is provided for this purpose.

(2) Open L.T. A.C. switch.

(3) Close the shunt-field switch with rheostat all cut out.

(4) Close the D C. circuit-breaker and main switch of some polarity.

(5) Start the rotary converter by closing the starting switch, cutting out the starting resistance slowly. If the machine rotates in the wrong direction, reverse either field or armature connections. Check polarity of windings before putting the machine in service, if any change in connections has been made If H.T. synchronising, close L.T. A C. main switch whilst the machine is running on the first starting contact.

(6) Adjust the speed of the converter to synchronous speed by means of the field rheostat.

(7) Phase out machine as described before.

(8) When the lamps or synchroscope indicates synchronism, close the alternating-current switches connecting machine to the line; this should automatically trip the D.C. breaker (to prevent the rotary being overloaded). Open the main and starting switches.

(**d**) **By Separate Motor :**—If starting from the alternating side is to be avoided and direct current not

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* A direct-current voltmeter, or incandescent lamps connected across the commutator brushes indicate by their beats the approach of the converter to synchronism.

always available, a separate starting motor, usually a small induction motor, (of less poles than the converter with squirrel-cage rotor) is used for starting the converter.

To avoid the necessity of synchronising the converter, by phase lamps, in the case of starting by direct current (which operation may be difficult where the direct current fluctuates, owing to heavy fluctuations of load, as railway systems), it is sometimes preferable to run the converter up to or beyond synchronism by direct current; then cut off from the direct current, open the field circuit, and connect it to the alternating system (in series with a suitable reactance to limit the instantaneous rush of current to a safe value), thus bringing it into step by alternating current By this the converter can be run up to and above the synchronous speed, and speed-regulating devices are arranged for synchronising the converter with the alternating-current supply mains.

This method of starting has the great advantage of requiring a relatively small starting current, and is used especially, when, because of limited capacity of generators or transmission system, it is essential to keep the starting current as low as possible.

The disadvantages of this method are that it requires time and skilled attendants to synchronise properly, and that the auxiliary motor adds to the cost and requires additional space.

189. To Start Rotary Converter to be Run in Parallel with Another :—

(1) In starting a second converter to be run in parallel with another. follow the same procedure as in starting a single converter.

(2) In building up the D. C. voltage, make sure that it builds converters, and the brush-holders are in similar position.

(3) If the starting method demands it, synchronise as usual.

If the machines are compound-wound, close the circuit-breakers, the equaliser switch and the main switch of the

same polarity in the order named, then adjust the voltage for paralleling.

190. Parallel Operation on the D. C. side :—The problem of load division in parallel operation of rotary converters, as in D. C. generators, is simply the problem of voltage adjustment. In the rotary converter, however, there are many more factors determining the voltage as compared with D. C. generator, and the problem is, therefore, more complicated.

The parallel operation of booster converters is as simple as the parallel operation of the shunt-wound D C. generators. The parallel operation of the shunt-wound generators is comparatively simple, although, if the inherent regulation differs unduly in two machines to be paralleled, any load fluctuations will not be proportionately divided between the two machines, the machine having the bigger voltage drop tending to maintain a steady load. The successful operation of compound-wound converters requires equaliser leads and proper operations between the resistances of series-field windings and connecting leads as D. C. generators. In addition, parallel operation of compound-wound converters is affected by the voltage ratio (from high-tension A. C. to D. C.) by shunt-field adjustment and by the reactance of the A. C. circuit.

191. Parallel Operation on Both Alternating and Direct-Current Sides :—It may sometimes appear convenient to connect several converters to the same low-tension A. C. busbars and the same D. C. busbars. With these connections, the A. C. and D. C. busbars close the electrical circuit between any pair of converters, and the direct-current load-division will be determined by the relative voltages generated by the several converters and by the relative resistances of the different parallel paths. Slightly different voltages in different converters will also cause large circulating currents in the closed electrical circuit which may damage the windings and even burn them out. Different converters rarely have the same voltage ratio, and it is very difficult to control the resistances of the various parallel circuits, since the brush

contact drops form a large part of the total resistances. The conditions become worse with converters of different ratings or design proportions. For these reasons converters must not be operated in parallel on both the A. C. and D. C sides

With the usual arrangements of separate step-down transformers for each converter the electrical circuits between different converters are interrupted and slight differences between the voltage ratios of different converters can be compensated for by corresponding differences in transformer ratios.

192. Load Division :—With two converters operating in parallel on the D. C. side, one of which takes less than its proportionate share of the load, the load may be equalised by one or a combination of the following adjustments :—

(*a*) The diverters on the series-field windings can be adjusted, decreasing the resistance of the one on the overloaded converter, if possible, or increasing the resistance of one on the underloaded converter. It should be borne in mind, however, that changing the ampere-turns in the series field by changing the diverter, changes the resistance of the complete field circuit. This change in resistance must be compensated for by a corresponding change in resistance in another part of the series-field circuit, so that the resistance of the total circuit remains unchanged. From another stand-point, a diverter on one converter series-field may be considered a diverter on both series fields, the effect varying only by reason of the resistance of the loads and busbars being added to one diverter circuit and not to the other

(*b*) If the relative ampere-turns are correct, but the series-field resistance differently proportioned, the resistance of the leads between the series and the equaliser busbars, can be changed, to compensate for a difference in the series circuit of the converter which taking more than its share of the load the resistance should be increased. The adjustment varies the resistance of one series field without introducing a third parallel circuit between the equaliser and the main busbars, and for this reason the adjustment is less complicated than in (*a*).

(*c*) The transformer ratio can be changed. This increases the voltage by the same amount throughout the range of load and will not correct for a difference in load varying with the voltage. An increase in no-load voltage of one converter will cause in that machine a greater increase in proportionate load and lighter loads.

(*d*) The reactance can be increased in the circuit of the lightly-loaded converter. This causes an increase in voltage and load that are proportional to the total load on the lightly-loaded unit. It is similar in effect to an increase in the number of series-field turns. It sometimes happens that reactances of converters in parallel are worked at different saturations so that the reactance voltages of the two converter circuits will have different ratios at light and heavy loads. This will cause the converter with the more highly saturated reactance to take less than its share of the load at heavy loads.

(*e*) The relative shunt-field currents of the two converters can be changed. The converter having the smaller ratio of series field to armature ampere-turns should have its shunt-field current increased. This will increase its no-load voltage (on account of change in power factor) and cause it to take a greater share of the load at light loads The voltages will tend to equalise as the load increases, a correct division being obtained at only one value of the load.

Since there are so many variables affecting load division, it is important to make a careful and systematic study of the particular case before making any such changes

Such a study should be conducted as follows :—

(*a*) Adjust the transformer ratios so that at no load and with shunt field adjusted to give equal power factors all converters have the same no-load D C voltage

(*b*) The series field should be adjusted by diverters, if possible, so that the ratio of series-field ampere-turns to armature ampere-turns is the same

(*c*) The resistance of series field (including diverter) *plus* the resistance of the leads from the series field to main busbar (positive or negative) should be adjusted so that the resistances are inversely proportional to the rated capacity of the converters.

(*d*) The reactances should be adjusted, if possible, so that the reactance volts of the various circuits throughout the range of load are equal. If they cannot be made equal, the series ampere-turns should be greater in the converter having the smaller reactance, to afford an approximate compensation. *It is possible to have exactly proportionate division of load when all four elements—transformer ratio, series ampere-turns, series-field resistance and reactance are properly proportioned.* Such complete similarity in transformers and converters rarely exists, however, but satisfactory load division can always be obtained, even if one or two of these elements are not correctly proportioned, providing compensating adjustments are made in the other elements and slight differences in wattless currents are satisfactory.

193 To Shut Down a Single Converter :—

(1) Open the D. C. breakers, thus taking the load off the machine. If the converter to be shut down is in parallel with others, shift as much load from it as possible by operating the field rheostat before opening the D. C. breakers.

(2) Open the D C. switches.

(3) Open the A. C. breakers.

(4) Open the A. C switches.

(5) Cut in all of the field rheostat resistance.

(6) See that the synchronising plugs, if any, are pulled out.

(7) Wipe off the commutator before the converter stops.

(8) Examine the brushes for defects and clean up the machine.

194. Emergency Precautions :—

(1) When converters flash over or the breakers trip out from excessive current, it is always wise to note the D. C. voltmeter before throwing in on the line again, as these troubles may cause a reversal of polarity in the fields making them build up in the opposite direction. If this should be the case, it will be necessary to reverse polarity or separately excite the shunt field.

(2) When the alternating-current power goes off for any reason, shut down the converter at once, opening all switches.

(3) When the A. C. breakers come out, open the D. C. breaker (if not tripped out automatically) and the switches, and then proceed to start as in first starting.

(4) When the converter flashes over and is thrown out of circuit, it is best, if possible, to shut down for a moment and examine the commutator, collector rings, and brushes, and clean up any burn which may have been caused. If this is not possible, the commutator can be cleaned after the converter has been put in service by exercising great care.

Caution :—Leave all switches open when the machine is not operating. When the shunt-field circuit of a rotary converter is excited, never open it quickly unless a path for the inductive discharge is provided. The circuit can be opened slowly, if desired, the arc at the opening serving to reduce the field current gradually. Do not permit any part of the body to bridge the opening or a serious shock will be received, better use but one hand, keeping all other parts of the body clear off the circuit. Always follow a fixed regular order in closing and opening switches, unless there are special reasons for departing from this order. A routine method will aid in avoiding mistakes. Close switches decisively keeping firm hold of the handle until completely closed. Keep small pieces of iron and bolts and tools away from the frame. Any such fragment attracted to the pole of a field magnet may jam between the armature and pole causing serious damage.

195. Hunting in a Synchronous Converter :—A rotary converter having no pulley and not being mechanically connected to machinery is more susceptible to oscillatory disturbances than a synchronous motor because of the light weight of its rotating parts. A sudden change of load on the synchronous motor is followed by series of oscillations giving rise to hunting. The hunting oscillations, once started, usually reach their maximum under given conditions in a few minutes of time. Hunting, which is approximately the same at all

loads, from no-load to over-load, is more troublesome when the field of the rotary converter is over-excited. Hunting is greater when several rotaries are supplied from an alternating-current generator than when a single-rotary converter is supplied, unless there are short A. C. mains between them or unless the converters supply direct current in parallel to the same direct-current mains. The cause of hunting, the methods of prevention of such oscillations, or of dampening them out, when once started, are also the same in both the cases.

196. Efficiency :—The efficiency of a synchronous converter which is usually greater than that of a motor or a generator having the same output is determined by loading, and increases as the number of alternating current rings is increased.

Let V=rated continuous voltage,

V_b =brush contact resistance drop,

I=the continuous-current output for which it is desired to calculate the efficiency,

W=the no-load input.

R_a =resistance of the armature winding as measured between continuous-current brushes,

K=the ratio of the copper loss in the armature conductors to the armature copper loss when the converter is operated as a continuous-current generator with the same output. Its value depends on the number of rings.

Then,

$$\text{Per cent. efficiency} = \frac{VI \times 100}{(V + V_b + KR_a)\, I + W}$$

197. Installation, Care, and Maintenance of Rotary Converters :—It is easily possible, by rough handling or careless use of bars or hooks to do more damage to a machine before or during erection, than it would receive in years of regular service.

It is to be borne in mind that the armature is liable to damage since its own weight is sufficient to crush the windings if it is lowered or swung against a

projection. Care is to be exercised in handling and installing rotary converters As moisture is an enemy of the insulation, a converter should not be allowed to stand where it can absorb moisture from the air or from any other source. A blow of any sort on part of the winding or of insertion into the machine of water, pieces of wire, tools, nuts, or foreign substances of any kind, by accident or otherwise, may cause a break-down or burn out, and should be avoided. It is desirable that all rotary converters should be assembled, installed and placed in operation under the supervision of an experienced engineer.

Unpacking :—When a rotary converter is shipped, entirely assembled, all boxing or crating should be removed and the machine is then ready for setting up and drying out. In cool weather the packing and wrapping should not be removed unless the apparatus has been long enough in the room where it is to be installed to come up to the temperature of the air.

If this precaution is neglected, the apparatus will sweat, and sufficient moisture may condense upon the windings to weaken the insulation and cause a break-down

When a converter is unpacked, it should be carefully examined to determine whether any damage was received in transit, and whether all parts and accessories are present in proper condition and position.

198. Location of Machines :—It is of greatest importance that in laying out a substation, the location of the converters be governed largely by the following considerations :—

(1) The machine should not be exposed to moisture from any source of escaping steam, or condensation of atmospheric moisture on overhead glass or a metal roof.

(2) They should not be exposed to the corrosive action of acid fumes or other injurious gases.

(3) They should not be exposed to dirt.

(4) Since the total temperature and, consequently, the capacity of the machine, depends upon the temperature of

the surrounding air, it is evident that the location should be in a room as cool and well ventilated as is consistent with proper protection from dirt and moisture.

(5) The position of converter should always be such that the commutator and the collector rings, which require special attention, are readily accessible for inspection.

199. Foundations :—The foundation is carried down to a solid bottom or is made of sufficient area to prevent sinking or displacement under the full weight it is expected to support.

Concrete piers are used to prevent vibration and to minimise the wear on the bearings and brushes. Care is to be taken that all pits in the concrete are properly drained and that passages remaining for cables and wiring are easily accessible and so laid out that the work of installing and connecting up will be simplified in every possible way.

200. Erection :--

(1) The bed plate is set on its foundation and levelled up by wedging. In cementing the bed plate to the foundation a mixture of one part of Portland cement and two parts of sand or half cement and half sand are used ; either of these gives good results. The cement and sand are first mixed dry and then water added until a very thin solution is obtained. A dam is constructed around the bed plate and the solution poured under it, continuing the process until the cement stands about $\frac{1}{2}$ inch above the bottom of the bed plate. The entire operation of mixing and pouring the cement is carried on without interruption and as rapidly as possible until completed, otherwise the cement first poured under the bed plate may partially set and prevent that poured later from flowing freely to all parts. When the cement has sufficiently hardened, the surplus is removed from the outside and the joint under the bed plate smoothened up

(2) Then the lower half on the frame and the bearing pedestals are placed in position on the bed plate.

(3) The protective coating from the shaft is removed, the journals cleaned, dried and then covered with a

film of oil. The bearings are thoroughly cleaned of grit or dust and covered with a film of oil. The rotating parts are next lowered into the bearings after which the oil-rings are seen whether they are in position or not. The upper half of the bearing is now put and seen that the oil-rings are free to move. Then the bolts are filled in and screwed after ascertaining that the armature is free to move in position.

When handling the armature it should always be supported by means of rope sligs about the shaft taking care that these do not come in contact with the end connections of the windings or damage that portion of the shaft which normally rests in the bearings. Any roughness at this point would cut the babit of the bearings and cause undue heating when the machine is in operation.

Never, under any conditions, should the weight of the armature be supported from the commutator or collector rings either by ropes or blocking. In putting the armature into position care must be taken not to scratch the bearings or bend the oil-rings.

(4) Clean the contact surfaces of the frame and set the upper half of the frame in position and secure it to lower half by means of bolts.

(5) Place the two halves of the direct-current brush-holder rocker rings in position. The individual brush-holder arms are bolted to the rocker ring and the individual brush-holders are bolted to the arms.

(6) The field, the alternating current and the direct-current armature leads are now connected up. The brushes are inserted in their holders after grinding them in with glass paper. It is next seen that the brushes move freely in the holders and are held under an equal and moderate pressure. After this the machine is connected to the switchboard including the connections of the overspeed device.

201. Drying Out Insulation :—In case the armature windings or field coils become damp due to absorbing

of moisture due to rain, snow or any such thing, then these are dried out as follows:—

(1) Block the rotor so that it cannot turn, raise the direct-current brushes, short-circuit the field and apply approximately 10 % of the normal alternating-current voltage to the slip-rings.

(2) Drive the converter perferably at a low speed (say, about 25 % of normal) from some external source, such as a separately belted motor, raise the D C. brushes and short-circuit the A. C. terminals, using a very weak field excitation.

(3) The field coils may be dried up by applying from some spearate source of excitation approximately $\frac{2}{3}$rds of the normal D. C. voltage with the rotary standing.

There is always danger of serious injury to the windings when drying out with current, since the heat generated in the inner parts is not readily dissipated; furthermore, coils containing moisture are much more susceptible to injury from overheating than when thoroughly dry. The temperature of all accessible parts should be carefully observed during the drying-out process and never allowed to exceed 80 degrees centigrade total temperature. Several hours or even days may be required for thoroughly drying out large machines. A curve should be plotted from the temperature and the insulation resistance readings, so that the progress of the drying out can be seen

If a machine of 600 volts or less shows an insulation resistance of approximately one megohm, both hot and when cooled down again, the drying is completed and the machine can be put into service. Continued running generally improves (that is, increases) the insulation resistance if the machine is kept clean.

202. Shaft Currents:—Under some condition sa difference of potential along the shaft may be set up which would cause a current to flow through the circuit consisting of shaft, bearings, pedestals and bed plates. This current may be sufficiently large to pit the shaft and bearings and cause trouble In order to prevent this, the pedestal at the collar end of the machine is insulated from the bed plate.

203. Earthing:—Except in very special cases, the frame of every machine is thoroughly connected to a good and permanent earth.

204. Grinding in Brushes:—The bearing of each carbon brush should be carefully filed to the curvature of the commutator; this can be done by putting the brushes in the brush-holder and drawing a strip of glass paper under each brush while pressing it firmly against the commutator.

The glass paper should cut in brush only on the forward stroke, and in the direction of normal revolution.

205. Adjustment of Direct-Current Brushes:—The D. C. brushes used in synchronous converters are usually of the graphitic type. This grade of brush is practically free from carbon or hard gritty material. Among its important characteristics are—high current carrying capacity, high lubricating quality, low friction-coefficient and consequently low losses and low resistance drop. The absence of abrasive qualities makes this type of brush unsuited for non-undercut commutators, where the mica must be worn down by the brush. The low resistance drop also makes it in some cases unsuited for non-commutating pole machines, which inherently have relatively high voltages induced in the armature coils undergoing commutation, producing large currents in the low resistance brush face.

The brush-holder arms and the brush-holders are correctly spaced and adjusted before the machine leaves the works of the makers; but, due to subsequent dis-assembling or rough handling during shipment, they may be displaced These adjustments have to be checked, in all cases before the machine is put in service. The brush-holder arms should usually have a clearance, of approximately $\frac{1}{8}$ inch, between the surface of the commutator and the bottom of the holder; and the relative spacing of the brush arms around the commutator, as determined from the edges of the brushes, must be uniform The preferable method of checking this latter point is to stretch a piece of paper tape around the commutator under the brushes, allowing the end to overlap to some

extent. Care must be taken that it is smooth and parallel with the edge of the commutator at all points. Make a fine clear mark with a sharp pencil on the tape exactly at the toe of the brush on each arm resting on the tape. Some marks of identification should also be made so that, after removing the tape from the machine, the arms corresponding to the marks may be readily identified. Remove the tape and measure the spaces between the marks, adjusting the arms until approximately equal spacing results. Brushes must be ground in as indicated in the preceding paragraph before and after spacing. The difference in spacing should not be more than $\frac{1}{16}$ inch. The brush-holder springs should be adjusted to a uniform tension of from $1\frac{1}{2}$ to $2\frac{1}{2}$ lbs. per square inch of brush-contact depending on the grade of brush and condition of operation.

206. Adjustment of Alternating-Current Brushes:—The slip-rings of all standard rotary converters are fitted with self-lubricating brushes either of the metal-graphite or plain graphitic type The former are made from finely powdered metal (mainly copper) and graphite, compressed under high pressure and then machined to size These have a very low contact drop. The brushes on each ring are staggered by means of plates put between the brush-boxes and the supporting bracket, so that each pair of brushes just covers the ring when at rest. Should the brushes be staggered too little or too much, the result will be a shoulder formed or the ring or the brushes which may lead to sparking and unsatisfactory operation. Care should also be taken to see that no dust is allowed to accumulate between the brush and the holder, as this will prevent the brush from moving freely and again lead to sparking. The brushes should be ground in by passing glass paper between the brush and the ring in the direction of rotation only; and the rotary should be run on light load (say $\frac{1}{4}$ - $\frac{1}{2}$ load) to allow the brushes to get thoroughly bedded. During this run the brush tension may be increased above the normal so as to shorten the time of wearing in.

207. Testing Brush Pressure:—In normal operation the brushes should have sufficient tension on them to ensure good contact with the rings, and should any brush be found to take more than its fare share of the current and heat up too much, its tension should be reduced. In adjusting the tension, consideration must be given to the position of the brush, *i e* , whether its weight assists or opposes the spring.

After cleaning the machines for general daily maintenance, the brush pressures are carefully tested and adjusted. About 2 to 2·5 lbs/ sq. in. is allowed for the commutator brushes and 4 lbs /sq. in for the slip-ring brushes. The pressure is tested by a spring balance, but the greatest care has to be taken in holding it correctly. It should be pulled in the direction of brushes It is best desired to place the hook of the spring balance under the contact of brush-holder spring. We have to test the pressures often while it is running and it shall be found that the readings for different positions of the hook and different directions of pulling often vary, hence the necessity of pulling in correct direction

208. Notes on Testing Carbon Brushes:—The following characteristics should be noted when testing the relative merits of various brushes :—(1) commutation should be good. This should be noted, after the brushes have had time to settle in. There should be no sparking or chattering and it is also advisable to measure the rise in temperature of the commutator after, say, two hours' running, as a brush does not operate satisfactorily if excessive heat is generated. (2) Before fitting a trial set of brushes it is most essential that the commutator should be toned perfectly smooth.

Noteworthy Practical Details and Troubles in Rotary Converters.

209. Staggering of Brush Rows:—The brush rows are staggered, one row is placed about $\frac{1}{8}''$ from the end of the commutator surface, the second row about $\frac{1}{2}''$ and the third row about $\frac{3}{4}''$.

The fourth set is again $\frac{1}{8}''$ from the end of the com-
This causes a uniform wear of the commutator

210. Bedding of Brushes:—When the brushes are new, they have got a flat surface and so do not make good contact all over the surface with the commutator ; hence, we put the soft carborandum paper, with every side on the top, under the brushes. The pressure on the brush is reduced and the machine is given a slight start from the A. C. side. Thus the brushes will wear away to form the desired circular arc as to fit the commutator surface uniformly.

211. Reverse Running of Rotaries:—Sometime, while starting a rotary for the first time after installation, it is found to run in a wrong direction. In this case, the remedy lies in changing over the shunt-field connections. The standard rotation for B. T. H. rotaries in Esplanade sub-station is anti-clockwise, whereas that of Metrovicar's rotaries is clockwise, when viewed from the common side.

212. Direct-Current Brush Position:—In non-commutating pole machines the correct running position of the brushes is in front of the no-load neutral when running A. C. D. C. (behind when running D. C. A. C.), and is found by trial. In commutating pole machines the brush position is on the neutral. The position of the neutral is always marked on the yoke and brush rocker rings.

213. Location of Neutral Point:—The no-load "neutral" point on the commutator is that point at which a minimum voltage is induced between adjacent commutator bars when the machine is running without load with only the main pole windings excited.

In case it is necessary to check the location of the "neutral point" one of the following methods should be followed :—

On non-commutating pole machines the neutral should be found while running the machine as shunt motor from the D.C. end or by driving the machine by some external power with the shunt-field winding excited. Use a low-reading voltmeter with 5-1·5 and 15 volts scales preferably. Use two carbon points for making contacts Hold the points, one commutator bar

width apart, on the commutator and more along until the point of minimum voltage is located

This method is not the most accurate, but is usually satisfactory for non-commutating machines.

For commutating pole machines the " Kick-neutral " method is the one most commonly used.

214. The " Kick-Neutral ":—This method is based on the fact that when the field circuit of any direct-current machine is opened, an induced voltage is generated in the armature windings. In case the brushes are in the exact neutral position, the resultant voltage is zero.

In checking this, set the brushes as close as possible to the mechanical neutral position. On all machines this is determined by placing the slots containing the top and bottom halves of a given armature coil equidistant from main poles and by moving the brush-rocker until the brushes on one arm cover the commutator bars connected to this coil. Raise all brushes and insert on each arm one brush whose face has been bevelled to practically a knife-edge so that each brush touches one commutator bar only. This edge should be parallel to the brush arm, and in the centre of the face of the brush. Arrange to excite, separately, the shunt field from any convenient source of power with about 20 per cent. of the normal current and with a quick break switch in the circuit. A low-reading voltmeter as before should be used, but connected across two brush arms of opposite polarity Open and close the field switch and note deflection on meter. The deflection, if any, will be only a momentary " kick." If the voltage is not zero, it indicates that the brushes are not on neutral and should be moved by shifting the rocker ring to such a position that no deflection will be obtained on the voltmeter when the field is opened or closed.

215. The Speed Limit Device :—As a safeguard against overspeeds, a speed limit device is attached to the oscillator end of the shaft, consisting of a spring-closed switch. When the converter reaches a certain speed above normal, a centrifugal governor mechanism operates the switch and opens the circuit-breakers, thus cutting off the converter from its source of supply.

To reset the switch it is merely necessary to move the catch lever back to the normal position by hand. This can readily be done at any time, whether the machine is running or not, by means of the lifting rod.

216. Adjustment of Speed-Limit Device:—When testing for overspeed the synchronous converter can be run as a motor from the D. C. side. It is important to have complete control of the speed during test. Use a tachometer or any direct-reading speed indicator, but do not use the ordinary revolving speed counter. The switch should trip at 10 % above synchronous speed. Bring the speed up slowly and watch for the tripping speed of the plunger. The tripping speed is raised or lowered by adjusting the two nuts on the end of the plunger, so as to further compress or release the plunger spring. The nuts should be given about one-half turn at each run until the switch trips at the desired speed. Care must be taken that the two nuts are securely locked against each other before running the rotary. Before starting each test see that the catch lever is in, and press the plunger several times by hand to see that it works freely.

217. Inspection:—Speed-limit devices should be operated at regular intervals as a part of the routine inspection to ensure that all parts are operative and all circuits complete. Failure to maintain properly the overspeed device and wiring may result in the destruction of a machine.

218. Side Play:—Over and above the staggering of brushes, as said before, the rotary converter machine is arranged to have a side play and serves the same purpose as a staggering of brushes This is accomplished by means of a stiff spring resting horizontally on the end of the machine shaft and a disc screwed in the pedestal. This disc being screwed in and out adjusts the amount of side play. Generally, the total travel of side play is about $\frac{3}{4}''$ in all machines.

It is often found that the rotary on being started does not begin this side play; the operator has to see this; and if found so, he gives a slight push to the plunger,

with a disc head and projecting outside from the end pedestal. This gives a push to the shaft. Once this is done, it continues its side play due to action of the spring.

219. The Mechanical Oscillator :—It is a self-contained device carried out at the end of the shaft to eliminate brush grooves in the commutator due to the armature running in a fixed position The operating parts consist of a hardened steel plate with a circular ball race, backed by a spring. This is not quite parallel to the face of the end of the shaft The steel plate is adjusted so that the ball, when at its lowest position, is in light contact with the race and shaft. As the armature revolves, the ball is carried upward and, owing to the convergence of the steel race and shaft face, the spring is compressed. The reaction of the spring forces the armature exactly away from its natural position and allows the ball to drop back to its lowest position in the race. The frame of a self-contained converter is dowelled to the bed plate in such a position with respect to the armature core that there is a magnetic pull holding the shaft end against the oscillator. Therefore, when the oscillator ball forces the armature away from the oscillator, this magnetic attraction returns the armature to its original position and the cycle is repeated.

To adjust the oscillator, unscrew its sleeve until the shaft runs free with the field excited. Measure the end play each way ; the running position of the armature should be off-centre towards the oscillator, or from the free running position the end play should be less towards the oscillator than opposite to it.

220. Connections for Parallel Operation :—In wiring up converters for parallel operation on the D. C. side the following precautions should be observed :—

(1) Connect the A. C. leads from the step-down transformers to switches and converters terminals corresponding to those of the other converters.

(2) Place the D. C. brush-holder arms in the same relative position with respect to the field poles as those in the other converters, and run the positive, negative and equaliser busbars of other converters.

(3) See that the field wires are brought out to the terminals corresponding to those of the other converters and connected in the same way.

(4) Be sure that the voltmeter lead from the positive terminal goes to the positive busbar and the negative to the negative busbar.

(5) In case of doubt as to the relation of the phase of the machine and the busbars the machine should be " phased out ".

221. **Main Direct-Current Leads :**—If the converters are of the same size and make, the only features requiring special attention is to see that all the cables leading from the various machines to the busbars are of equal resistance. This means that if the machines are at different distances from the switchboard, different sizes of cable should be used, or resistance inserted in low resistance leads. If the converters differ in design or size, the matter requires more attention. In this case the difference in potential or drop in voltage between the terminals of the machine and the busbars to which they are connected should be exactly the same for every converter when each is carrying its proper share of the load. To secure the best results, the total drop between converter terminals and switchboard must not only be the same at equal loads but the drop in corresponding sections of the connecting cables of the different machines should also be equal, *i.e.*, the drop in the positive lead from any one converter at full load should equal the drop in each of the other positive leads when carrying full load. The same condition should be secured in the negative leads, in the equaliser connections and in the series-field windings It may be necessary in achieving the desired results to alter the length or size of connecting cables and occasionally additional resistance is required.

The equaliser lead must have as little resistance as is practicable, and for this reason it is the usual practice to make the equaliser leads with the same cross-section as the main leads.

222. **Care and Maintenance :**—At all times keep the rotary converter clean and free from oil and dust, especially from copper or carbon dust.

With high voltage machines a small accumulation of dust on the windings may be the cause of a serious burn-out. In stations of sufficient size, like Esplanade, to warrant the expense it is advisable to instal an air pump for supplying compressed air, with a piping system so distributed that a short section of hose will enable the attendant to reach all parts of the winding on any machine to blow off the dust. The pressure used in such service should not exceed 25 lbs. per square inch as a high pressure may lift the insulation wrappings and blow dust inside the coils.

Always allow any accumulation of water in the pipes to be blown out before turning the air blast on the machine.

In blowing out machines, adjacent machines should be protected from flying dust by a suitable cover or shield. Where insulated parts, subject to copper or carbon dust are accessible, they should be wiped clean with a dry cloth in addition to blowing out as described above. It will facilitate the cleaning of insulated parts if they are painted with insulating varnish at regular intervals. Before painting any part it should first be cleaned thoroughly. At the time selected for painting, the machine should be given a suitable high-voltage insulation test to locate possible weakness at a time when they can be conveniently repaired.

223. **Daily Cleaning and Maintenance:**—All the machines in all sub-stations of B. E S T. are daily attended to. Commutator is everyday cleaned with a piece of cloth. They are cleaned weekly after some heavy short circuits or overloads by No. 0 glass paper The interval of this cleaning depends upon the nature of the load, line of running, etc. The glass papers or sand papers are fixed on the curved surface of a block of wood. They are clamped on the sides by iron plates fitted with butterfly nuts. If the condition of the commutator is entirely bad or uneven, it is ground. The apparatus is similar in shape to the sand-papering block with the exception of carborandum paper instead of which there is a grinding stone. Often the commutator may be

grinded with a grinding stone run by a motor. Commutator, if very badly worn, may be required to be turned. For sand papering, the machine is started from the A. C. side and then disconnected The block is applied with a good pressure on the commutator surface.

224. **Bearings :**—When first starting a machine, particular attention must be given to the bearings to see that they are well supplied with lubricant. The oil-rings should revolve freely and carry oil to the tops of the journals. It is well to allow a new machine to run for an hour or two with no load, and to watch the bearings closely for any indications of undue heating. The bearings of most machines are generally liberal in size and with proper care will not give trouble. They may, however, be made to overheat by any of the following causes :—

(1) Insufficient lubrication which may be owing to (*a*) poor lubricant, (*b*) insufficient quantity, (*c*) failure of oil-rings to revolve.

(2) Poor aligning of levelling, causing excessive end-thrust or binding

(3) Rough bearing surface which may be caused by careless handling or the presence of dirt or gritty substances in the oil or grease.

(4) Bent shaft.

A heating is usually safe if it operates at a constant temperature below 70° C. The rapid rise of temperature towards this limit, however, is a danger signal calling for prompt attention. A bearing may be hot enough to burn the hand held against the outside for a few seconds and yet be below the temperature and safe to run. It will seldom be necessary to do more than to supply a hot bearing with an abundance of fresh clean lubricant, making certain that the oil reaches the bearing surface. If this is not effective, pour a heavy lubricant directly into the journal, and should this not be sufficient, take load off the machine and keep the rotating part in motion enough to prevent the bearing from becoming set or frozen. In normal service, the oil should be withdrawn from the bearings occasionally, and fresh oil substituted, running enough of the fresh oil, through the bearings

to wash out all sediments. The old oil, as well as that used for rinsing, can be run through a filter and used again. A good oil filter is a necessity in every plant where much machinery is in use. The frequency with which the bearing must be refilled depends so much on local conditions such as the severity and continuity of the service, the room temperature, the state of cleanliness, etc., that there is no definiteness about this. Until local conditions show another interval to be suitable bearing should be refiled every six months

225. Blocking of Rotary Converter Commutators :—The rotary converter commutator requires much greater attention than any other commutating machine owing to the flashing-over and other tendencies of this machine. The process consists in grinding the commutator or the slip-rings with a glass paper which is mounted on a block. The machine is run for a second or two and then switched off immediately. At this time, when the armature is revolving under its kinetic energy, the glass paper block is pressed over the commutator or slip-ring, the block being cut to fit the curvature of commutator or slip-ring as the case may be. The block is moved along the entire length of the commutator. Thus, it is daily smoothened and kept fit and smooth for service.

Emery cloth or paper should never be used for this purpose on account of the continued abrasive action of the emery, which becomes embedded in the copper bars and brushes. Even when glass paper is used, the machine should be thoroughly blown afterwards and no particles should be allowed to remain there.

226. Commutator Grinding :—If the commutator is in very bad condition, it may be necessary to use a turning tool ; but, for ordinary cases, a motor-driven grindstone is used for grinding The machine should be run at from 100 to 120 % of the normal speed. Where a revolving wheel is used, much lower speeds give better results, turning requires a still lower speed It should not be higher than 150 ft./min. Before grinding a commutator the machine should have been running a sufficient length of time to bring the temperature up to a constant value. It should then be shut down and

the bolts holding the commutator V-ring should be tightened. The commutator should then be ground or turned down to a true surface. Before grinding, the brushes should be lifted off the commutator as the copper and stone dust will rapidly wear them away. The dust will also become embedded in the brush contact surface and latter damage the commutator or cause poor commutation. The armature winding should also be thoroughly protected during this operation to prevent an accumulation of dirt and metal chips, which may result in an insulation failure when the machine is again put in service. The protection can usually be best obtained by using a circular shield of fuller board or similar material around the commutator at the end next to the armature This shield can be easily supported from the brush-holder arms and should extend from the commutator at the end next to armature to an inch or two above the surface of the armature. It may also be desirable to put a temporary canvas board over the armature winding. After grinding, the machine should be thoroughly cleaned by blowing out with dry compressed air or by wiping up with waster before replacing it in service or by both.

227. Circuit-Breaker Protection :—

(1) *Reverse Direct Current* :—Whenever there is a source of D. C in parallel with a synchronous converter that is also independent of the high-tension A. C feeder serving the converter, a relay should be provided that will open D C. breaker in case the D. C. reverses. Such an independent source of D. C. may be a D. C generator, a storage battery, or other synchronous converters, usually in other substations, fed from the same or different generators, but connected in parallel through continuous feeders or trolley circuits. The relay should be tested periodically.

(2) *Interlocking A. C. and D. C. Breakers* :—With all converters the breakers should be so arranged that the D. C. breakers will open whenever the A. C. breakers will open. In some traction sub-station, the conditions are such that short circuits occur on the trolley circuits that

are so severe that the rotary converter flashes and the arc holds until the alternating-current breaker is opened. If the conditions cannot be improved by the insertion of resistance in the trolley feeders, or by other means, the converter should be protected from burning by interlocking the breakers so that the A. C breaker is opened automatically whenever the D. C. breaker opens. Obviously, if this is done, the D. C. breaker should be set so that it will open only when severe short circuits occur. Protection against ordinary overloads should be provided by lower setting of feeder-breakers. The selective action between the feeder-breakers may be obtained either by a difference in current setting or in time setting (if means for time adjustment are provided). In this connection it should be remembered that in the case of severe short circuit, the current increases so rapidly compared with the speed, at which the breaker opens, that the current increases far beyond the current for which the breaker is set.

In the case of a short circuit immediately outside the sub-station the current may easily reach to ten times the normal rated current, assuming the ordinary types of carbon circuit-breakers are in use, and this current value will be practically independent of the circuit-breaker setting Some synchronous converter will satisfactorily commutate very large momentary currents, provided the machine circuit-breaker does not open ; while they will flash with no greater currents, if the machine circuit-breaker does open. This is an additional reason for high setting of machine-breakers when the machine can be properly protected from long continued overloads by lower setting of feeder-breakers or other means.

228. Troubles and Remedies :—

Sparking at the Brushes :—It may be due to any of the following causes :—

(*a*) Brushes incorrectly set with reference to the neutral point, correct setting is of particular importance in commutating pole converters.

(*b*) Brushes of improper characteristics.

(*c*) Defective electrical design.
(*d*) Hunting.
(*e*) Severe overloads or extreme variation in load.
(*f*) In non-commutating pole converters, low alternating voltage with large direct-current loads.
(*g*) Brush-holders insufficiently supported.
(*h*) Brushes stuck in holders or inaccurately fitted to commutator.
(*i*) Improper brush tension
(*j*) Rough commutator due to high bars, to high mica or flat spots.

229. Bucking or Flashing :—In traction supplies overloads and short circuits are very common Sudden overload on traction side results in a very great and sudden increase of current of D. C. side of the rotary converter Owing to the reactance present on the A. C. side in the transformers and in the lines, the A C. current input to the rotary converter cannot immediately attain the required high value. This upsets the balance or neutralisation of A C. and D C currents in the armature and the commutation, especially at the peak-load time, (when the loads are already high), becomes insufficient. This gives rise to sparking. Sparking on the rotary converter at peak-load time is not uncommon For the same reasons as above, sometimes, when a sudden short circuit occurs on the traction side, it sets up an E.M.F. which is sufficient to form an arc between the adjacent brush spindles This is termed a 'flash-over.' This then travels further, and thus continuous ring of arcing is formed right round the commutator on its periphery when once formed This is maintained as the interlinking air gets ionised and thus forms an easy path for arcing. It may be brought about by any condition causing excessive voltage in the coils short-circuited by the brush or between adjacent commutator bars or may be caused by abnormally low surface resistance on the commutator between adjacent brush arms Any condition tending to produce poor commutation increases the likelihood of bucking. Excessive voltage under the brush is usually caused by short circuit of varying degree Most direct-current machines will flash if short-circuited at the terminals

and the direct-current voltage is maintained. Short circuits in service usually occur on the line, so that some resistance exists between the short and the machine, thereby limiting the current. Taps from feeders to trolley should always be located some distance from the substation. Excessive voltage between commutator bars is caused directly by increased line voltage or is indirectly caused by extreme current overloads which distort the field flux. Increased line voltage may be due to disturbances on the high-tension distributing system induced by lighting switching, short circuit, etc. A decrease in the insulation strength between brush arms may be due to the presence of conducting gases Ordinary types of circuit-breakers do not act quickly enough to protect machines from abnormal changes in current or voltage. On short circuits, for example, the current increases far beyond the setting of the breakers before the circuit is finally opened

230 Constructional Means to Prevent Flash-Overs:—The following means are adopted to prevent this in the construction of rotary converter :—

(*a*) Magnetic blow-outs like those described for tram car control, as prevent flash-over by blowing the arc out radially from the commutator surface. (*b*) Air blast fans are arranged to blow out a conducting vapour formed after a fiash-over. The fan is in the form of small blades or wings fixed on the armature end. Thus the air passes over the armature, cools it, and thus does the desired blasting effect on the commutator as a safeguard against flash-overs. Chief point to note in this type is that the armature and the commutator peripheries are on the same level. It will be noted that this is never the case, with other D. C. machines. For this particular case, however, in order that the blast should effect with full efficiency on the commutator, the above construction is evident. (*c*) Bearing pedestals and base plates are installed to prevent an arc between the commutator and the earthed metal. In some machines we have insulated bed plate and only one pedestal, adjacent to the commutator, as this appears to be sufficient. (*d*) The brush yoke does net over-hang the commutator, being well insulated from

it and from brush-holders. (*e*) In some of the Metro-vicar's machines we have ebonite flash barriers, fitted between the adjacent brush spindles, with hardly $\frac{1}{4}''$ clearance from the commutator. (*f*) In Railway traction, high-speed D. C. circuit-breakers are installed to interrupt short circuits before they have had sufficient time to take effect on rotary converters.

231. Reactance Used as a Protection Against Short Circuits:—Shunt-wound synchronous converters may be protected from the effects of short circuits by inserting reactance in the alternating-current loads.

Motor Converter

232. Motor Converter:—The motor converter consists of an induction motor with wound rotor and a rotary converter which behaves like a D. C generator mounted on the same shaft, and there is electrical connection without slip-rings between the rotor of the motor and the armature of the generator, a hollow shaft being employed for connecting the short-connecting leads. The motor is supplied with A. C. power It transforms a part of it into mechanical power delivered to the shaft, and also acts as a transformer delivering the rest of the power in electrical form at a lower frequency from its secondary to the armature of the converter, the exact division of the power depending on the relative number of poles in the motor and the converter. The speed of the motor converter depends upon the supply frequency and varies inversely as the sum of the number of poles in both machines. As in the case of rotary converter, the use of a large number of phases is an advantage.

There are three or six slip-rings for the purpose of starting and there is a short-circuiting ring to short-circuit the twelve-phase when the synchronous speed is attained.

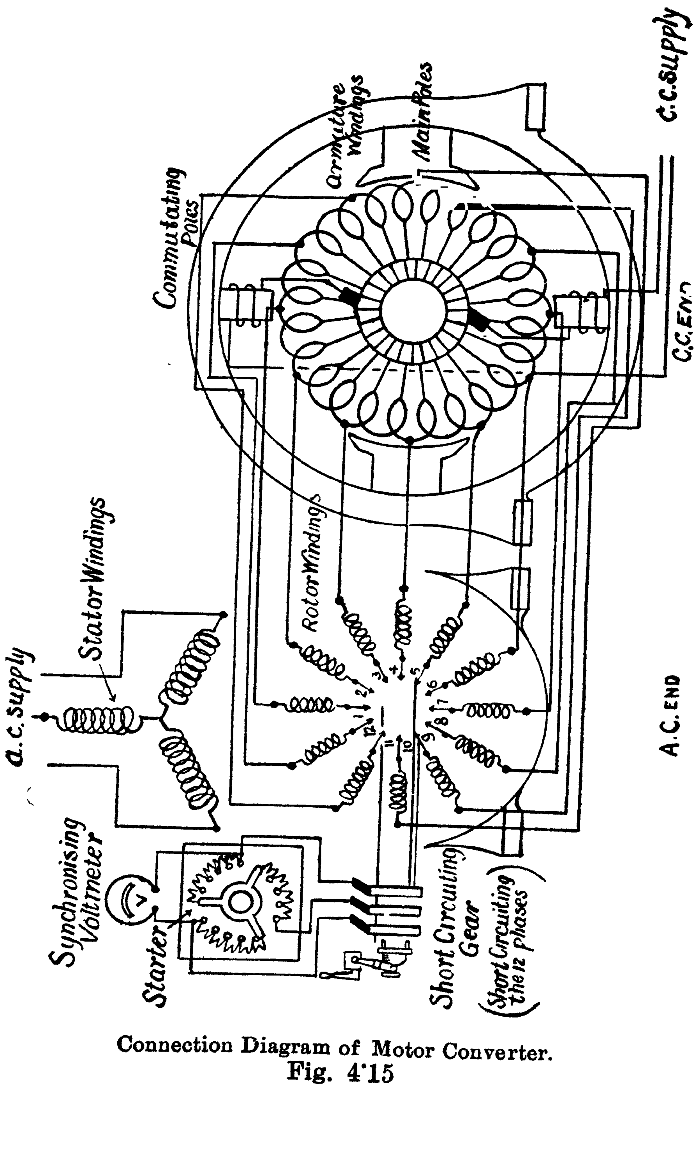
The advantageous feature of the motor converter, as compared with synchronous converter, specially at a high frequency, is that the former may be fed with alternating current of any frequency and at any electromotive force and that it will deliver direct current from the commutator operating at a frequency best adapted for satisfactory performance.

233. Principle :—Suppose that the set is running at a definite speed and has equal number of poles in the field system of each machine. The E. M. F. in the rotor corresponds in phase and magnitude to the slip. and its frequency is directly proportional to the slip.

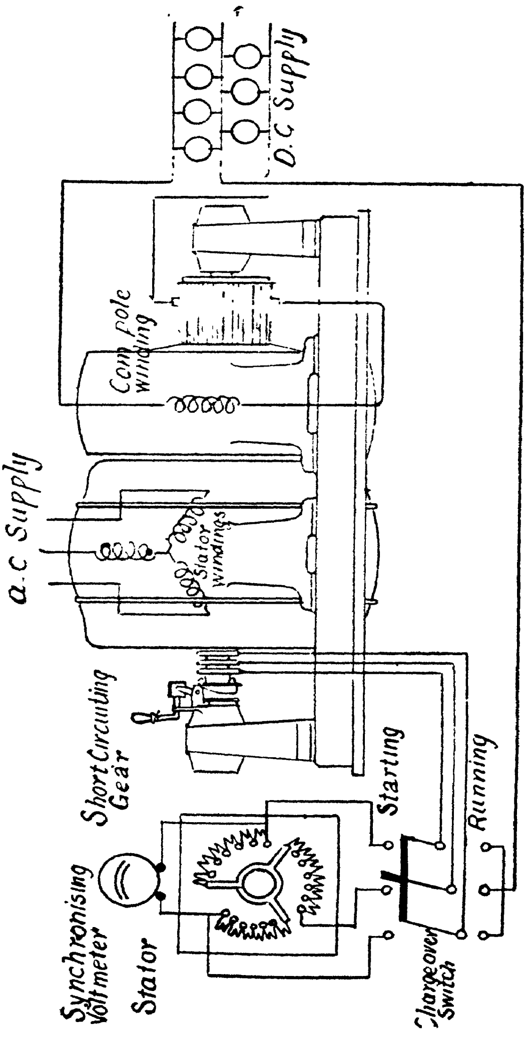
Due to the electrical connection between the rotor and the armature of the generator the E. M. Fs. in the rotor will produce currents in the generator, but since its armature rotates in a magnetic field, another series of E. M. Fs. are induced in it. The frequency of the E. M. Fs. due to the rotor is that of the slip, but the frequency of the E. M. Fs. due to the generator action is that determined by the speed. If these two frequencies are the same, the rotor must run with a slip of 50 per cent. or the set must run at half the synchronous speed. For any difference in speed, there will be a circulating current flowing round the two rotating elements and a large synchronising force is produced to make the two frequencies equal. Hence, the normal running speed of the set is half the synchronous speed, and it acts like a single synchronous machine.

Again, as the motor is rotating with a slip of 50 per cent., its efficiency, when so running, is 50 per cent., neglecting the stator losses Half the power input is thus transformed into mechanical form by the ordinary motor action and this is utilised in driving the generator through the rigid coupling and the remaining half is transmitted to rotor by transformer action and the electrical power so developed in the rotor is supplied to the armature of the D. C. generator and helps to drive it by rotary converter action. The power which is given out by the commutator and is received by the line in the D.C. form, is the sum of the two effects just described—the A.C. side operating half as an induction motor and half as a transformer and the D.C. end operating half as a generator and half as a rotary converter.

234. Speed, Frequency and Number of Poles:—The number of poles in the field systems of the two machines need not be the same.



Connection Diagram of Motor Converter.
Fig. 4·15



Connection to Load.

Fig. 4·16.

Let P_m = number of poles in the induction motor.
P_g = number of poles in the D. C. generator.
N = number of revolution per minute.
f = frequency of supply.
f_s = frequency of slip.

Speed of induction motor

$$=\frac{f-f_s}{P_m}\times 120$$

$$\therefore \quad f_s = f-\frac{NP_m}{120}$$

The frequency of D. C. generator

$$= f_s = \frac{N\,P_g}{120}.$$

$$\therefore \quad f_s = f-NP_m/120 = NP_g/120$$

$$\text{or, } NP_m+NP_g = 120\,f.$$

$$\therefore \quad N = 120f/(P_m+P_g)$$

Thus, we find that the machine runs at a speed equal to the synchronous speed of an induction motor having as many poles as there are in both the A.C. and D C. ends.

The frequency of the current in the D.C. generator is $f_s = \{120\,f/(P_m+P_g)\}\times P_g/120 = f\times P_g/(P_m+P_g)$. The D. C. side is thus always operating on a frequency considerably lower than that of the supply, which is an advantage, as the performance of converters is better the lower the frequency.

235. Power Transmitted Mechanically and Electrically :—Consider the A.C. side,

$$\frac{\text{Mechanical rotor output}}{\text{Electrical rotor input}} = \frac{\text{Actual speed}}{\text{Synchronous speed}}.$$

$$=\{120\,f\,(P_m+P_g)\}\div 120\,f\,P_m$$

$\therefore$ Mechanical output of rotor = total input $\times P_m/(P_m+P_g)$, neglecting the stator losses.

$P_m/(P_m+P_g)$ is the fraction of the total power converted by motor generator action. The power received by the D. C. side in the electrical form = Power developed electrically by the rotor, and is equal to :—

$$\frac{\text{Electrical power developed in the rotor}}{\text{Rotor input}}$$

$$= \frac{\text{Speed of slip}}{\text{Synchronous speed}} = f_s / f.$$

But, $f_s = f \times P_g / (P_m + P_g)$

$\therefore$ the electrical power developed in the rotor

$$= \text{Rotor input} \times \frac{f \times P_g \, (P_m + P_g)}{f}$$

$$= \text{Total input} \times P_g \, (P_m + P_g)$$

$P_g \, (P_m + P_g)$ is the fraction of the total power converted by transformer and rotary converter action.

$$\text{Synchronous speed} = \frac{\text{Line frequency} \times 120}{\text{Sum of poles of both elements}} \times \text{(R. P. M)}$$

$$\text{Rotor frequency} = \text{Line frequency} - \left(\frac{\text{Primary poles}}{120}\right) \times \text{(R. P. M.) (cycles per sec.)}$$

Power transformed electrically

$$= \text{Total output} \left(\frac{\text{Secondary poles}}{\text{Total poles}}\right)$$

Power transmitted mechanically

$$= \text{Total output} \left(\frac{\text{Primary poles}}{\text{Total poles}}\right)$$

When the number of poles of both the elements are equal, as is usually the case, those relations become very simple,

236. Starting of Motor Converter :—It can be started from the A. C. or D. C. side. To start from the A. C. side, a three-phase starter in the rotor circuit is necessary to start the induction motor of the converter

and a synchronising voltmeter is used across two of the rotor slip-rings. The remaining phases are disconnected during starting. The D. C. part of the machine is arranged to be self-exciting, and its field builds up as the set comes up to speed.

After the main switch is closed, the rotor circuit of the induction element is closed through the starting resistance. As the rotor begins to revolve, two alternating currents are superimposed in the rotor circuits, one at the maximum frequency decreasing with the speed, due to the induction element, and the other at the minimum frequency increasing with the speed due to the commutating element. The latter current is appreciable only near synchronism or, in the case of separate direct-current excitation, in the secondary elements. As the rotor approaches the normal running speed, these two currents approach the same frequency which is indicated by a slow oscillation of the needle of the voltmeter connected in the starting circuit. The neutral points of all the rotary phases are connected together and the starting brushes lifted from the rings by a mechanical device.

By proper selection of the starting resistance, the starting current may be maintained at the low value throughout the entire starting operation. Due to the small armature current during starting, the direct-current voltage will always build up with the correct polarity.

The set tends to approach its subsynchronous speed and the alteration in phase of the rotor and armature E. M. Fs. become slower and slower ; at the moment the voltmeter needle passes through zero, and when correct speed is attained, the starter is short-circuited and the set will thereafter operate synchronously. An additional short-circuiting switch, which is then closed, connects the remaining phase to the neutral point. The set is now ready for running on load. An ordinary motor starter is used to start the machine from the D. C. side. The A. C. side is synchronised at the proper speed like an alternator.

237. Application as a Power Factor Improver :—When started up and synchronised from the

A. C. side, while D. C. side is over-excited and left disconnected from the bar, the set can be used as a power factor improver.

238. Comparison of Motor Converter, Motor Generator and Rotary Converter:—The power factor of motor converter is better than that of an induction motor generator. It has good commutation owing to the relatively low speed of the machine; there is simplicity in starting and operation; it does not require transformers at ordinary voltages. It has decided advantages over the rotary converter above a frequency of 40. It is not liable to reversal of polarity as in the case of rotary converter. The stator of the induction motor can be wound for any voltage. It can be used to supply a three-wire system without a balancer as it can take care of unbalanced current to a great extent.

In respect of starting characteristics, the motor converter is superior to either a synchronous converter or a synchronous motor generator set. It is the equivalent of an induction motor generator set. It is less expensive to construct and is $2\frac{1}{2}$ °/o more efficient in operation.

A motor generator set may consist of either a self-starting synchronous or an induction motor and either a shunt or a compound generator. Self-starting synchronous motors are usually used in motor generator sets of 500 kW. or more; induction motors are ordinarily used for 100 kW. or less on account of their simplicity; and between 100 and 500 kW. either motors may be used depending on conditions under which it is used.

Advantages of Motor Converter over Rotary Converter:—Some of the advantages of motor converters over rotary converters for the higher frequencies in commercial use are given below:—

Reliability:—The frequency of currents in the rotor and armature of a motor converter is generally half that of the main supply, and the number of poles of the D. C. corresponds only to half the supply frequency. Thus the motor converter has the advantage of a low-frequency machine. Now it is well-known that the design, manufacture and operation of a low-frequency converter are a simple proposition comparatively, and such

machines usually give entirely satisfactory results. Therefore, the greater reliability of the motor converter, compared with the rotary converter on the higher frequency circuits, is not difficult to understand, and it has been freely commented on by the actual users of both types of plants.

The possibility of the flashing-over with the rotary converter is largely due to the fact that it is impossible to get so great a distance between the brush spindles as is obtainable with a motor converter of similar output. The reason for this is, that rotary converters, with such a number of poles as would allow of the spacing between brush arms being similar to that on a motor converter designed for the same A. C. and D. C. conditions, would have a commutator speed much higher than what the limits of present-day practice permit. Consequently, with the rotary converter the best possible compromise has to be adopted.

Simplicity:—One of the first points which arise in considering the installation of converting plant is the question of simplicity of operation. Converting plants are usually installed in sub-stations more or less widely separated from the main generating station or else in consumer's premises and especially in the latter case it is not always practicable to employ skilled supervision on account of the heavy expense entailed. In view of this, the acknowledged greater simplicity of the motor converter, compared with the rotary converter, is, from the purchaser's point of view, a matter of considerable importance.

The motor converter is self-contained, the whole conversion taking place within the combined set, partly electrically and partly mechanically, and with these machines no transformers are necessary and no heavy A. C. cable connections or complicated switchgear required.

The operation of starting up a motor converter has already been dealt with, but attention may here be drawn to the fact that this operation is practically identical with that of a plain induction motor generator—admittedly the simplest type of rotating converting plant, while the

switchgear for a motor converter is generally similar to that required for an induction motor generator, in which switchgear is much more simple in addition to being less costly than that required for a rotary converter.

Floor Space:—This is frequently a point of considerable importance (though not absolutely in India) and it is interesting to note that the floor space occupied by a motor converter is usually less than that required by a rotary converter and its transformers, even though the rotary is running at a higher speed ; the motor converter does not require transformers.

Reversal of Polarity:—Motor converters are not liable to reverse their polarity at starting up or on short-circuit, but this is a contingency which frequently gives trouble with the rotary converter, necessitating the use of additional switchgear not required with the motor converter, but even then it is frequently found necessary to entirely disconnect the rotary field and correct the excitation of the machine from an external D. C. supply when such is available, and this, of course, is a troublesome matter.

Starting and Synchronising:—The usual synchronising gear required is a single voltmeter and a low-tension two-pole short-circuiting swith. Motor converters are also made of the self-synchronising type, the only addition to the ordinary equipment being only a small choke coil with the necessary isolating switch.

Upkeep:—Cost of renewal of brushes and upkeep of commutator and slip-rings are less, since the speed is less, and since the diameter of the commutator is small and also of the slip-rings, the number of brushes is small.

Speed:—Low speed and hence more reliability.

Absence of Noise in Operation:—This is not a point to be much stressed. Since the speed is less, the diameter of the commutator small, and the number of brushes is few, the noise is lesser.

Voltage Variation:—In the case of the motor converter, they can work even if the supply voltage falls to a much less degree.

Power Factor:—Motor converters designed for unity power factor at full load have a much higher power factor at the lower loads than rotary converters designed for unity power factor at full load. Motor converters can be designed to give leading power factor and in this way further improve the total power factor of the system.

Efficiency:—Rotary converters have a higher full-load efficiency than motor converter, but at $\frac{3}{4}$ full load and at lower loads, there is very little difference. Under ordinary conditions the over-all efficiency, year in and year out, is about the same for the two types.

Flexibility of Operation:—Motor converter designed to operate normally from A. C. to D. C and running in parallel with other plant on D. C. side, will, in the event of the A. C. supply being interupted, reverse automatically and supply the A. C. system until matters have been put right.

239. A Comparison of M. C. with R. C. and M. G. Type: Induction Motor Generator: Advantages:—Self-starting can be wound for any frequency and (except in the smallest sizes) operate direct on high-tension supply. Reliability of operation, simplicity of control gear, skilled attention not necessary, can deal with wide voltage range on the D. C. side without the addition of boosters or rather corresponding apparatus. Freedom from reversal of polarity or flashing over.

Disadvantages:—Considerably lower efficiency than either the rotary converter or the motor converter. Lagging power factor, unless a compensator is installed, can only operate from A. C. to D. C.

Type:—Synchronous Motor Generator: Advantages:—Can be wound for any frequency (except in the smallest sizes)—operate direct on the high-tension supply—reliability of operation at unity or leading power factor—can deal with wide voltage range on D. C. side without the addition of boosters or other corresponding apparatus—can supply alternate current and D. C. also as desired, *i.e.*, can run inverted—freedom from reversal of polarity or flashing over.

Disadvantages :—Considerably lower efficiency than either motor converter or rotary converter. Must be started from the D. C. side by means of a separate induction motor excepting with synchronous motors of the self-starting type—danger of dropping out of step on occasion of H. T. disturbances.

Type :—The Rotary Converter : Advantages :—High efficiency—power factor approximately unity or slightly leading—low initial cost especially with modern high-speed types.

Disadvantages :—They cannot run direct on high-tension supply and transformers must be provided. Only a small amount of voltage regulation can be obtained on the D. C. side unless a booster or other corresponding apparatus provided—usually run at higher speeds than M. C.—consequently the peripheral speed of the commutator is greater and there is considerably more wear of commutator and brushes—frequently noisy in operation, especially at high speeds.

A. C. slip-rings and brush gear have to deal with the load of the machine continuously and consequently they are much larger and heavier than with motor converter. The peripheral speed of the slip-rings is much greater and there is considerably more wear of slip-rings and brushes.

Maintenance charges are higher than the motor converter.

Usually there will be greater number of poles than the motor converter necessitating thereby close spacing of D. C. brush arms and special type of brush gear.

Liability of reversal of polarity when starting from the A. C. side and also on short circuits. Liability of flashing over on heavy over-loads.

Type :—Motor Converter : Advantages :—Frequency of currents in armature generally half that of A. C. supply, therefore the number of poles of D. C. end correspond to half the supply frequency with consequent wide spacing of brush arms—self-starting—usually run at lower speeds than the rotary converter—much less noisy in operation than rotary converter.

High Efficiency :—Can be wound for any frequency and except in the smallest sizes, operate direct on igh-tension line.

Reliability of operation--unity of leading power factor—simplicity of control gear, skilled attention not needed—can deal with wide range of voltage on D. C. side without the addition of boosters and other corresponding apparatus.

Freedom from reversal of polarity and the maintenance charges are negligible.

Disadvantages :—Initial price usually slightly higher than rotary converter on account of appreciably lower speeds, but this is more than out-weighed by the large number of advantages.

* Transverter

240 Description :—This is a recent development of a re-converter. It derives its name from the fact that it serves the function of a transformer and a rotary converter. The main difference between this and a rotary converter is that the later has got a rotating armature winding of a rotating commutator with stationary brush gear—while the former has a stationary ring winding connected to a stationary commutator over which is the D. C. collecting brush gear. The transverter has a stationary ring winding connected to a stationary commutator over which the D. C. collecting brushes rotate.

In the rotary converter a uniform D. C. voltage is obtained because the sum of the E. M. Fs. between the points on the rotating winding connected to the D. C. brushes, is the same at every moment. In the case of a transverter the same end is obtained by inducing multiphase E. M. F. in a stationary winding connected to a stationary commutator with rotating brushes.

All other windings of a transverter being stationary they can be cheaply and easily cooled and insulated by immersing in oil with effective cooling arrangement. As

* Adopted from Meares and Neal's Electrical Engineering Practice, Vol. II, 1927.

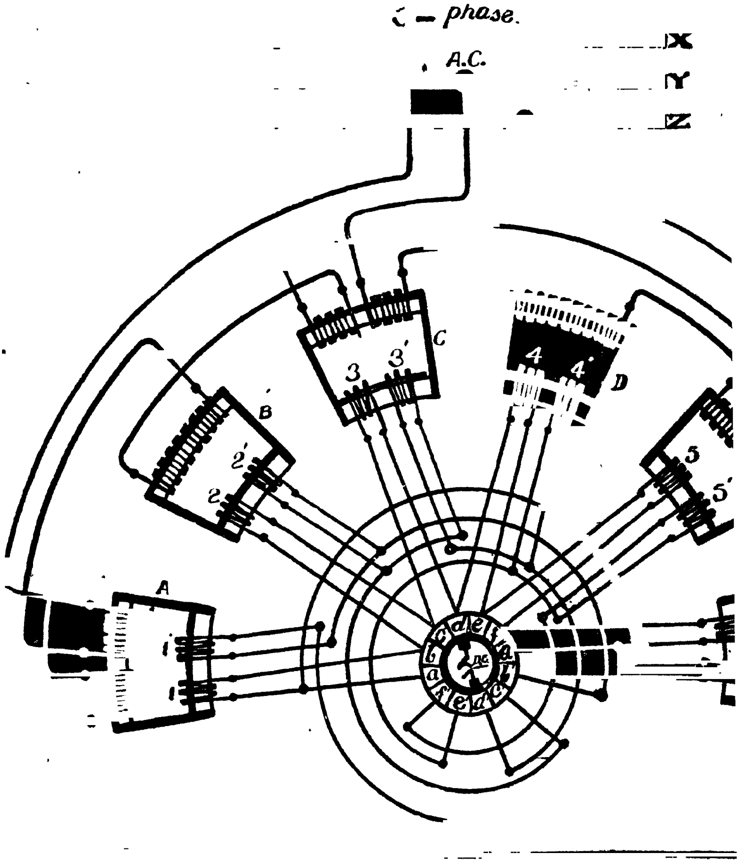
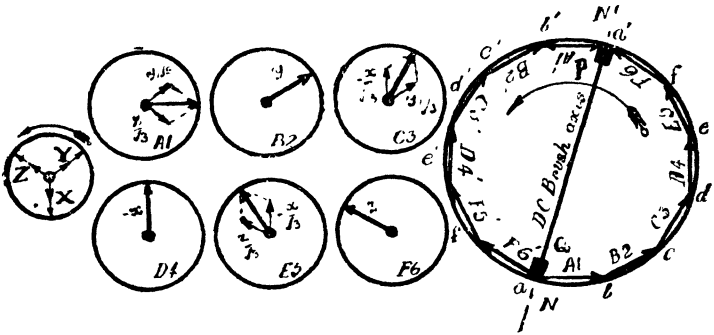


Fig. 4·17.

To

the commutator is stationary, insulation for high voltages is facilitated and the mechanical difficulties associated with high speed rotation of commutators dealing with high power are eliminated. The rotating brushes are connected to slip-rings, and by connecting a number of commutators in series, very high D. C. voltages can be obtained.



Vector Diagrams illustrating the Action of Phase multiplying Transformers in a Transverter.

Fig. 4·18

241. The Principle of the Transverter :—There are six transformers A to F, as shown in the Fig. 4 17, each with two secondary windings 1, 1′, 2, 2′, etc. The secondary coil is connected between the commutator segments a, b, and the coil 1′ is connected in reversed polarity between segments a', b', opposite to a, b ; similarly, coil 2 is connected to b, c, while 2′ is connected in opposite polarity between b', c', and so on The connection of the primaries to the three-phase supply is also shown in the Fig. 4·17.

It is important to note that the transformers B, D & F have single primary coils of w turns each, whilst A, C, E. each has two primary coils with $w/\sqrt{3}$ turns in each.

The three phases X, Y, Z, are, as would be evident from the diagram, connected in star, and can be represented by vector diagram of E. M. Fs. as at the left of Fig 4·18.

Suppose that the primary coil of w turns on transformer B induces an E. M. F. x in the secondary coil 2; in the transformer A at that moment an E. M. F. equal to $x/\sqrt{3}$ due to $w/\sqrt{3}$ turns in the phase Y will be induced in the secondary coil 1. Similarly, in the transformer C, there is induced an E. M. F. $x/\sqrt{3}$ in coil 3 by $w/\sqrt{3}$ primary turns in phase Y. The transformer A has a second primary winding connected in opposite polarity in phase Z; the E M. F. induced in coil 1 by this primary is $-z/\sqrt{3}$; hence the resultant E. M. F. in coil 1 due to the action of both primary coils is as shown at $A1$. Similarly there is induced in coil 3 an E. M. F. $=x/\sqrt{3}$ due to $w/\sqrt{3}$ turns in reversed polarity in phase X; the resultant E. M. F. in coil 5 is, therefore, as shown at $C3$. Considering coils 1, 2, and 6 in the same way, it will be seen that the primary E. M. F., X, Y, and Z induced in the coils 1 to 6 equals resultant E M. F's. differing 30° in phase; these E. M. F's., being applied between the commutator bars a, b, c, etc., correspond to the vector diagrams shown to the left of the axis NN. At the instant considered P would be the positive and Q the negative brush of the commutator, and if the brush axis NN be rotated synchronously with the primary phases X, Y, Z, the polarity of P and Q will remain constant and so will the E. M. F. between them, *i.e.*, a steady D. C. voltage will be available between P and Q. The value of this voltage is dependent on the value of the A. C. voltage and the ratio of the transformers A to F.

If 2, 3 or 4 times as many commutator bars as there are secondary windings on the transformer are used, each secondary coils being then connected between 2, 3, or 4 pairs of equidistant bars, the angle between the brushes is reduced from 180° to 90°, 60°, or 15° in the respective cases and the necessary speed of rotation of the brush gears is reduced to $\frac{1}{2}$, $\frac{1}{3}$, or $\frac{1}{4}$ of the synchronous speed required in the case to which Figs. 4·17 and 4·18 refer.

By using more transformers and further subdividing the primary windings a greater number of secondary

phases and a lower voltage between adjacent commutator bars, can be obtained ; the principle of operation remains the same.

Where a number of commutators are connected in series, the secondary ring windings to which they are connected may be on a single set of transformers with a single set of primary windings.

Hence, we find from the explanation given above that a transverter consists of a large number of standard components assembled together, each of which is simple in itself.

This machine is still at the experimental stage, and is very interesting and promising development. Its **principal application** will probably be—

(1) In the conversion of A. C. at generator voltage (say 3,000 to 11,000 volts) to D. C. at, say, 100,000 volts for transmission.
(2) In re-converting it to either to A. C. or to D. C. at lower voltage (*e.g.*, 1,500 volts for traction purposes).
(3) As a link between A. C. systems independent of the frequencies of the latter.

Thus, according to requirements, a transverter makes possible the advantages of D. C. transmission (elimination of power factor, capacity and inductance effects with reduced stress on insulation) with advantages of A. C. generation and distribution (no rotating commutator and easy change of voltage by static transformer.

The transverter is reversible, *i.e.*, it can convert D. C. to A. C. ; and by connecting a second set of secondary windings on transformer to a second commutator, the transformer primaries being excited by A. C and the two sets of brush gear being rotated synchronously, D. C. energy can be supplied to one commutator and drawn off from the other at a different voltage.

The largest transverter built is supposed to be of 2,000 kW. capacity Such machines will be particularly useful in connection with the transmission of comparatively low power over relatively long distance as required by main

line electrification schemes. The efficiency of a 2,000 kW. transverter converting 6,000 volts, 3 phase, 50, A C. D. C. at 100,000 is 95 to 96 % at all loads from half to full load, and 90 % to 93 % at $\frac{1}{4}$ load and about 60 % at $\frac{1}{10}$ load. On full load the loss is about 3 % in the transformers and about 2 % by windage

Exercises

(1) The continuous voltage of a synchronous converter is 440. Find the alternating voltage (neglecting resistance drop) between adjacent rings when the converter is provided with (*a*) 2 rings, (*b*) 3 rings, (*c*) 6 rings.

(2) Calculate the current in the alternating-current mains when the output of the converter in Ex. 1 is 1,000 amperes, the efficieney 93 per cent. and the power factor 95 per cent.

(3) The power factor of a 2-ring converter is unity and the continuous-current output 200 amperes. Determine the maximum (instantaneous) current flowing in a conductor. Power factor is (*a*) unity, (*b*) ·86.

(4) The continuous voltage of a 100 kW., 3-ring converter is 500, the resistance of its armature (measured between continuous-current brushes) is 0·25, and the no-load input, when operated as a continuous-current motor without load (at rated speed and normal field excitation), is 3·1 kW. Calculate the efficiencies for 25, 50, 75, 100, and 125 per cent. of rated output, and plot the efficiency curve (using per cent. of rated output as abscissa).

(5) A compound-wound 50-cycle, 3-ring converter has an inductance connected in each alternating-current supply line. When the input to the converter is 100 kW., the power factor of the converter is unity and the voltage between continuous-current brushes is 500. When the input to the converter is 10 kW., the power factor of the converter is 0·5 and the voltage between continuous-current brushes is 450. Find (*a*) the value of the inductance in the alternating-current lines, (*b*) the voltage of the alternating-current supply system.

(6) Explain the switchboard connections that must be made in a sub-station containing self-synchronising rotary converters, and compare the advantages of this type of converter with that in which the rotary is started up without this special device. Give a diagram of connections of the self-synchronising rotary, and explain the method of starting up.

(7) A dynamometer voltmeter and a permanent magnet moving coil voltmeter were used simultaneously to measure the drop on the winding of the commutating poles of a rotary converter. A considerable difference was observed between the readings on the two instruments, although they read alike when connected together to a cell. Explain the probable reason for the difference in the readings, and say which instrument should give the higher readings, and why.

(8) A rotary converter with six slip-rings is fed from the secondaries of a three-phase transformer with star-connected primaries. Each primary coil has ten times as many turns as the secondary. A load of 100 amperes at 440 volts is taken from the rotary. Draw carefully a diagram of the connections, and also a vector diagram showing the magnitude and phase relationship of the voltages of the line, of the transformer coils, and of the slip-rings. Calculate approximately the voltages on the mains, and the currents in the primary coils if the power factor is ·9 and efficiency 100 per cent.

CHAPTER V

RECTIFIERS AND VALVES

Mercury Vapour Rectifiers

THE necessity of converting alternating to direct current in many cases, and the desirability of dispensing with running machinery in sub-stations, etc., has led to the development of the rectifying properties of the mercury vapour lamp for this purpose. Essentially the rectifier consists of an arc *in vacuo* between iron or carbon anodes and a mercury cathode, which allows the current to pass in one direction only, namely, from the anode to the cathode, as the names imply.

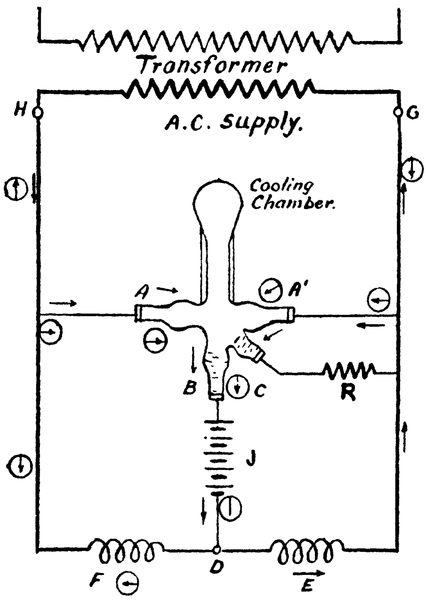


Fig. 5·01.

The exclusive use of mercury as a cathode is due to the fact that it can be vaporised, condensed and returned by gravity to the cathode during the operation of the arc, without loss of material; while the electrical conductivity of mercury vapour entails but a small voltage to maintain the arc and enables the anode to be well removed from the cathode, which is essential in order that the anode shall be kept cool.

242. Description :—It is essentially a receptacle of glass or steel from which air and all foreign gases have been exhausted and filled with mercury vapour at a low pressure. It contains one electrode of mercury B (Fig. 5·01) called the cathode and two other electrodes of graphite or iron A, A, projecting into the tube connected to single-phase or polyphase mains. The anodes are to be further apart the greater the current to be rectified. The complete equipment further consists of a source of alternating current HG and two coils E, F of high reactance having a low resistance. Generally, a starting or exciting electrode C or supplementary anode is connected to a smaller pool of mercury separated from the cathode by a small distance and a load, say, a battery.

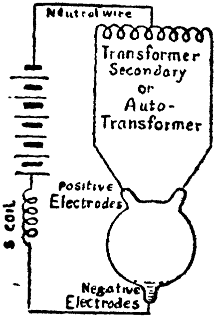


Fig. 5·02.

243. Principle, Operation and Connection :—In such a tube the mercury vapour, in common with almost all metallic vapours, offers (*i*) a very high resistance to a current which flows from the mercury to the graphite electrode, but (*ii*) a very low resistance to a current flowing in the opposite direction. In other words, it allows a current to pass easily in one direction and hardly at all in the opposite direction. Advantage is taken of this *selection of current* of mercury vapour in the construction of the mercury vapour arc rectifier. The operation depends, so to say, on the *valve action* of an arc in a mercury vapour. The complete phenomenon which occurs when such an arc is struck is shown in the figure 5·03. The arc begins at the anode, which is heated up, which is followed by a luminous column. Then we have a dark gap, finally a white hot cathode spot. This spot is the basis of the arc which travels in an irregular manner at a high speed over the cathode. With an ordinary mercury arc there will be, under this spot, a deep crater and a pale negative flame underneath. But in the case of a rectifier, this flame is undesirable. The mercury arc allows

current to pass only in one direction and, as stated, this unidirectional property, or, in other words, this valve action, is the main principle of operation of the rectifier.

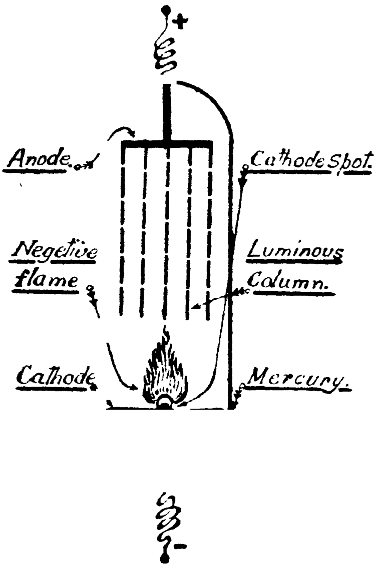


Fig. 5·03.

Connection :—The graphite electrodes are connected to the opposite sides of the lines from the transformer—Fig. 5·01. The high-reactance coils used for the purpose of preserving the arc when the voltage becomes zero. are connected across the transformer. The negative side of the battery to be charged or the arc to be lighted is connected to the middle point of the reactance coil and the positive side is joined to the large mercury pool at *B*. The small mercury pool *C* is connected through a resistance *R* to one side of the transformer line, as being somewhat away from *B* there is a high resistance between *C* and *B*. Hence, a stilting mechanism is provided to bring the edges of the mercury pools together closing an auxiliary circuit which offers a path to the current from the wire *G*, through resistance *R*, from *C* to *B*, through the battery to *D*, through half the reactance coil *F* to the other side of the current *H*. A spark or arc is formed, which, owing to rocking the bridge, is broken where the edges of mercury recede. This arc produces mercury vapour in the tube and so charges the receptacle with electricity. The resistance is cut down between the points A' and *B* and the points *A* and *H*. Hence, the current easily passes from either *A* or A' to *B* according as *A* or A' is positive at this instant. The arc jumps to one or the

other of the main anodes and alternates on these during regular operation. Once the rectifier starts, it will continue to work if the circuit contains proper inductance. If used for continuous excitation, the supplementary anode C is connected to a source of direct current.

To increase the rectifying power, keep the vapour pressure low by working at a low temperature or enclose the terminals in narrow chambers far removed from the mercury pool. Thus it may be taken as an "electrical valve" which permits current to flow only from a positive terminal to the pool of mercury. Any cause which lowers the vacuum will allow inverse current to be set up, or alternate half cycles of two phases differing

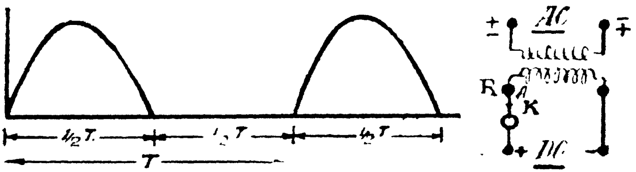


Fig 5'04

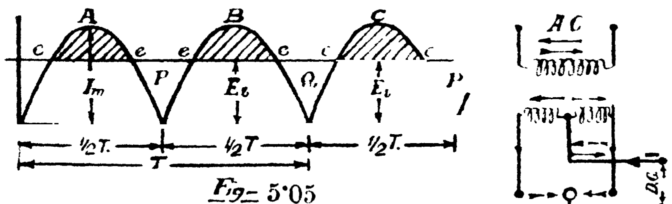


Fig 5'05

Fig-1 Rectification of Single phase AC by unilateral conductivity.

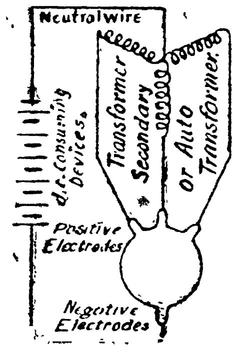
Fig-2 Rectified A.C.; both half waves of single phase supply.

180° in phase.

244. Single-Phase Rectifier :—Such a rectifier depending for its action on the unilateral conductivity gives only a pulsating rectified current that is half waves of A. C. separated by half periods during which no current flows, as shown in the Fig. 5'04. The R M.S value of such a wave is ·5 I_m and average value ·32 I_m, where I_m is the

maximum value. But if we use such means that, as in Fig. 5'05, both the half waves are utilised, we obtain unidirectional current as shown in the figure. In this case the R.M.S. value is '707 I_m and average value 0'64 I_m.

245. The three-phase rectifier differs from the single-phase rectifier only in this that it requires no inductance to sustain the direct-current wave.



The reactance coils E and F may not be necessary if a special transformer with large leakage reactance is used having the secondary divided into two equal coils (Fig. 5'06). Then the negative of the battery is connected with the middle point of these two secondary windings, which does the double function of the reactance coils E, F and of the transformer windings H, G'.

Fig. 5'06

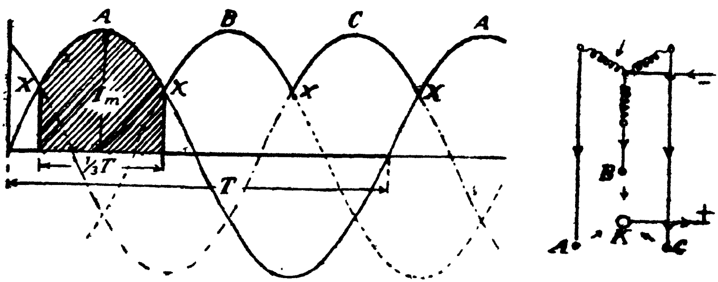


Fig. 5'07.
Rectified 6-phase A. C. alternate half cycles used.

A complete installation of mercury vopour arc rectifires is shown in Fig. 5'08.

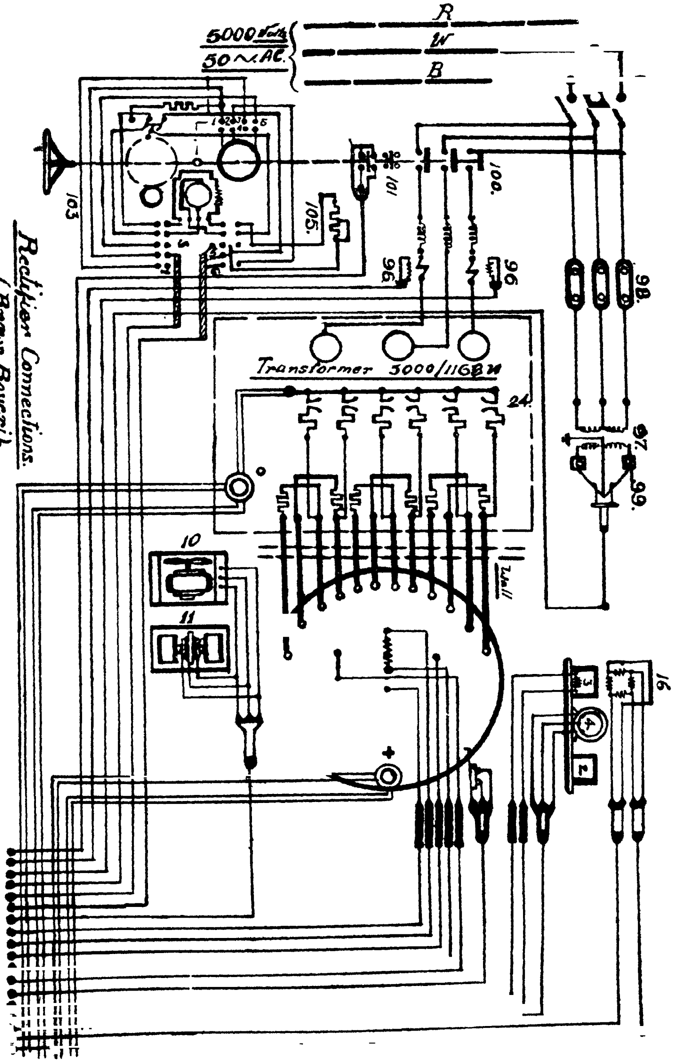

R
W
B
50 ~ AC.
103
105.
101
100.
96
98.
97.
99.
24.
10
11
16
Wall
Rectifier Connections.
(Brown Boveri)

Fig. 5'07 A.

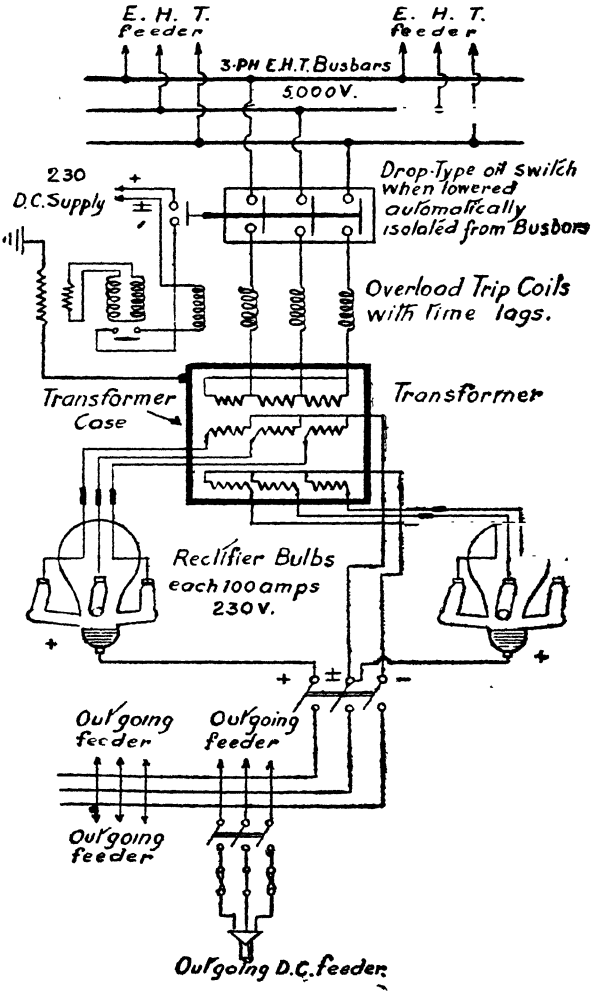

E. H. T.
feeder
E. H. T.
feeder
3-PH E.H.T. Busbars
5000V.
230
D.C. Supply
+
±
Drop-Type oil switch
when lowered
automatically
isolated from Busbars
Overload Trip Coils
with time lags.
Transformer
Case
Transformer
Rectifier Bulbs
each 100 amps
230 V.
+
+
+
±
−
Outgoing
feeder
Outgoing
feeder
Outgoing
feeder
Outgoing D.C. feeder

Fig. 5'08.

246. Polyphase Rectifiers:—In a 3-phase rectifier, as shown in Fig. 5'06, the current changes from the anode 1 to the anode 2 when the E. M. Fs. of 1 and 2 are equal and the resultant wave form is shown by the thick line in the figure. The R. M. S. value of such a wave is ·84 I_m and its arithmetical value is ·83 I_m. Thus each anode carries in turn current for one-third the period. But in the case of a six-phase rectifier (Fig. 5'09)

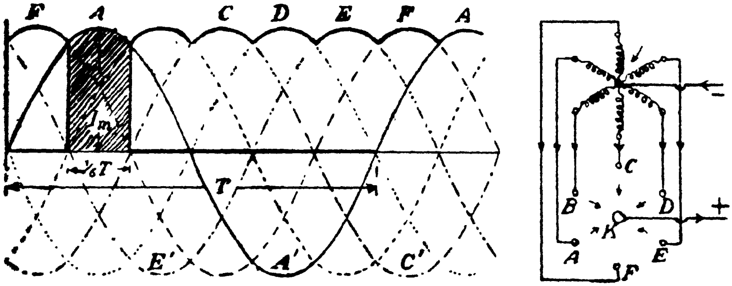


Fig. 5'09
Rectified 3-phase A. C. alternate half cycles used.

each anode carries for one-sixth the period. For such a rectifier the R.M.S. and average values are equal, being nearly ·95 I_m.

247. Efficiency:—The losses within the rectifier chamber are due to the voltage drops at the anode (about 5 volts), the cathode (about 9 volts) and in the arc (about 0'1 volt per cm. of arc length), making a constant total drop of about 20 volts in the rectifier. In consequence, the efficiency of the rectifier is practically independent of the load, while the higher the voltage the higher the efficiency—hence the suitability of such rectifiers for high-voltage D. C. traction.

The voltage drop is about 18 to 20 V in glass bulb rectifiers and 20 to 30 V in iron-clad rectifiers.

An empirical relation between the D. C. and A. C. voltages, *as given by Messrs. Meares and Neale*, is—

$E = aV + b$ volts, when
E=A. C. voltage

V=D. C. voltage
a=1·11 for single-phase, ·85 for 3-phase and ·74 for 6-phase.
b=18 to 20 for glass bulb rectifiers and 22 to 30 for iron-clad rectifiers.

To the A. C. phase voltage, as above calculated, must be added the voltage drop in the anode reactance coil, if such be used.

The drop in the rectifier being constant, the efficiency is practically constant at all loads, and rises with the D. C voltage. The efficiency is approximately 95 % for V=400 volts and 98 % when V=1,500 volts.

When calculating the *over-all efficiency*, allowance must be made for the losses in the transformer and auxiliary plant.

248. Transformer:—The greater the number of anodes the larger becomes the transformer for a given output, but the smaller the ripple in the D. C. voltage. Usually 6 anodes are used. The transformer for rectifier supply must be specially reinforced against short-circuits. With an absorption 'choke' a 6-anode rectifier needs a transformer rated only for a 3-anode rectifier.

At Kingsway the transformer steps down the voltage from 6,600 volts to the required amount and further more, the neutral point of the secondary winding provides the −ve D. C. pole. In the case of the single-phase equipment the −ve D. C. pole is obtained from the mid-point of the secondary winding.

249. Auxiliary Circuits :—It has been pointed out that the rectification takes place in the bulb owing to the oneway electron flow from the mercury cathode to the graphite anodes. This electron-flow must, however, be started through that bulb and for this purpose the bulb is fitted with an automatic starting and maintaining circuit.

At Kingsway the arrangement is to start the bulb by means of a starting flexible electrode placed just above the mercury cathode and controlled by an electro-magnet placed next to it but externally to the glass bulb

container. When the equipment is energised, this electrode is pulled into the mercury completing an electric circuit. The electrode is then released springing away from the H_g and interrupting the circuit and so causing a spark which begins the vaporisation of H_g, and sets the bulb in action.

Two other auxiliary electrodes act as exciters operating as a small independant rectifier and maintaining the necessary rate of vaporisation started by the starting electrode regardless of the amount of load carried by the main anodes.

The equipment can, therefore, deal with any load within its capacity down to zero load. These auxiliary circuits are fed from the auxiliary winding in the main transformer or from a separate auxiliary transformer.

250. Power Factor :—For a six-phase rectifier complete with reactance coils, etc., the power factor will vary from ·95 to ·9 from full to quarter load. For a 12-phase rectifier, the power factor varies from about ·9 at full load to ·8 at quarter load.

251. Regulation :—The rectifier has no inherent regulation, which depends largely on the connections. There are two aspects of the voltage regulation of a rectifier, namely—

(1) Variation of the D. C. voltage at any particular load.

(2) Change of the D. C. voltage as the load varies.

For each system of connection, there is a definite ratio between the A. C. voltage and the rectified D. C. voltage—

With a given A. C. voltage, the D. C. voltage can be varied by.

(1) Chocking coils in the anode leads.

(2) Variable tappings in the primary side of the transformer, or

(3) An induction regulator.

The last method is more costly, but it gives a continuous gradation of voltage.

By the use of voltage relays on the D. C. side, the A. C. voltage applied can be regulated, so that the variation in the D. C. voltage shall not exceed 1°/o at either end of a feeder. If required, the rectifier can be compounded so that it gives a constant or a rising voltage.

The four aspects of the regulation may be summarised as—

(1) Regulation due to reactance.
(2) Regulation due to resistance.
(3) Regulation due to loss in rectifier proper.
(4) Regulation due to impedance of source of energy.

In a rectifier which does not use any special devices to regulate the voltage characteristic, the D. C. voltage rises from 12 to 15 °/o from full load to lowest load which can be carried without the spark going out. But by using a special chocking coil L, as shown in the Fig. 5·11, we can obtain the voltage characteristic V which

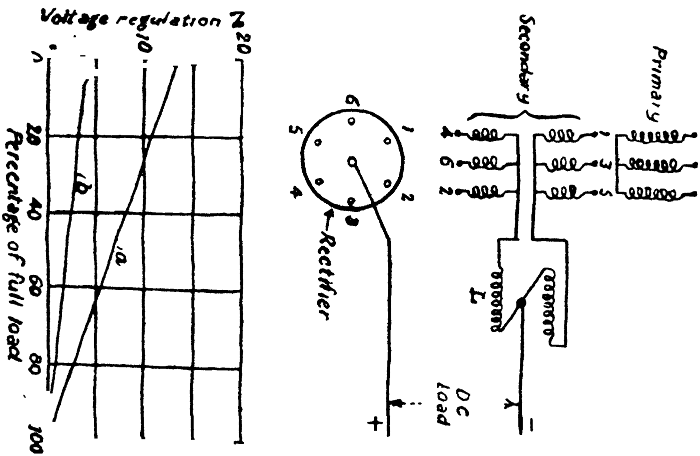


Fig. 5'11.

rises only by about 4 °/o from full load to 10 amperes and has a sharp rise of about 15 °/o as the load approaches zero. This sharp rise, of course, is negligible, because the rectifier is never in operation under such conditions.

252. Load Characteristics:—The rectifier, owing to its nature as a valve in contradistinction to that of a converting machine, is an apparatus with an inherent continuous rating. It has a large overload capacity, since it is free from mechanical inertia. The rating must be reduced where overloads of long duration are required, for although momentary overloads are easily handled, continuous overload will result in overheating with its consequent liability to the development of faults. It can respond quickly to load fluctuations owing to the comparative absence of the electrical inertia introduced by the presence of magnetic fields. A given rectifier will theoretically provide its rated current at any desired voltage, so that the kW. rating will depend directly upon the D. C. terminal voltage. In practice, however, the higher the rectified voltage, the greater becomes the tendency for short-circuits between anodes due to heating, and for 'arc-back,' etc., so that output current ratings are progressively reduced as the voltage is increased.

253. Troubles and Remedies:—'Arc-back,' or loss of rectifying property, depends largely upon the temperature rise due to a given load. The presence of foreign gases and failure of the vacuum reduce the voltage that the rectifier will withstand without arc-back. The fitting of an anode guard—consisting of an iron tube with open-mesh grating enclosing the anode—assists in suppressing the tendency to arc-back.

'Flashing' is momentary loss of valve property and is due to various causes such as the condensation of small globules of mercury on the cool anodes.

'Fading' occurs in glass-tube rectifiers with long arms, and is due to charges on the glass shielding the anodes.

254. Cooling:—Glass rectifiers are cooled naturally, by air fan, or by immersion in oil; metal-clad rectifiers by the circulation of water. Cooling is very important, since it determines the load, overload capacity, losses, etc. Short-circuits are caused by condensed mercury running down the anodes; by overheating of the anodes; by the

effect on the anodes of ultra-violet radiation from the cathode spot ; by insufficient vacuum and continuous abnormal overload causing overheating.

255. Advantages and Disadvantages of Mercury Arc Rectifiers :

The following are a few advantages :—

(1) Automatic and distant control operations are made possible, saving the cost of attendance.

(2) No synchronising devices necessary, thus increasing the speed of operation in starting.

(3) Practically a static silent apparatus, thus yielding higher efficiencies.

(4) Capacity for instantaneous short-circuit currents is good.

(5) Since the voltage drop is constant, the efficiency is higher the higher the D. C. voltage, ranging from 78 % at 65 volts to 99 % at 2000 volts.

The disadvantages :—

(1) It cannot take up overloads for long periods for the anode gets heated and 'backfiring' starts.

(2) The ripples in the rectified wave form.

Life :—Life depends upon the temperature at which the bulb is operated. The life is indefinitely long if the bulb is operated at a low temperature.

Use :—It is used when small current is required for :—

(1) Charging batteries from an A. C. supply.

(2) Supplying a certain series type of D. C. arc lamps from an A. C. supply. Here a current transformer supplies the current to the rectifier which delivers a direct current of constant value.

When large current is required for power and lighting, larger sizes rectifiers are to be used.

256. Classification :—Mercury vapour arc rectifiers can be mainly classified into two classes—(*a*) those having glass receptacles and (*b*) those having steel receptacles of comparatively large output.

257. Construction of Glass-bulb Rectifiers :— The first rectifiers were built with glass bulbs, and such are

still used for small powers, low voltages, currents up to 250 amperes and few anodes. Glass-bulb rectifiers have a long but unpredictable useful life. They must be discarded when the anodes have been worn sufficiently for the deposited material to hinder radiation and cause fading. The bulbs are evacuated during manufacture, when care is taken to eliminate occluded gases. Little knowledge of the state of the vacuum is possible during operation. Graphite anodes are usually employed, since they do not quickly deteriorate, and tend to absorb stray gases. Molybdenum or platinum must be embodied in the lead-in arrangements to form an efficient seal. The temperature of glass-tubes is limited to about 110° *C.*; above this temperature the internal arc-drop increases very rapidly. The arms of glass rectifiers are usually given a right-angle bend to protect the anodes from ultraviolet rays from the cathode and from contact with condensed mercury, both of which tend to cause short-circuits. Starting may be effected by tilting the bulb.

In Fig 5'12 a glass bulb *F*, which is evacuated, is fitted with two anodes *A* and *B* of carbon or iron and cathode

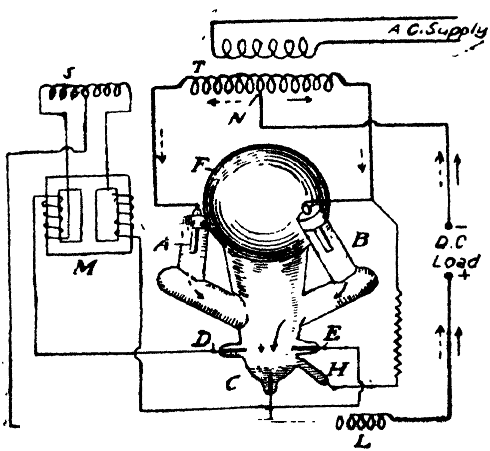


Fig. 5'12.

C of mercury. The rectifying action is due to the cathode which being hot enough emits electrons, the temperature of the hot spot where the arc touches the cathode being between 2,000° to 3,000°C and the anodes nowhere exceed a dull red heat, the temperature varying from 500° to 600°C, and are sometimes artificially cooled. The average temperature of rectifying chamber should not exceed about 75°C lest the vapour pressure should become too high.

The main constituents comprise (a) main transformer—Fig. 13, (b) the rectifier bulb.

The supply is stepped down or up according to the requirements to obtain the required pressure and is then passed through the rectifier bulb which acting as one way valve allows the current to flow in one direction only. Continuous current is thus obtained.

258. Bulb:—Fig. 5·14. The conversion proper takes place in the rectifier bulb which acts as a one way valve. The rectifier bulb comprises a highly evacuated bulb of glass fitted with graphitic anode electrodes for the A.C. inlet and a mercury cathode for the D. C. + ve outlet.

When the bulb is in operation, electrons are emitted from the mercury pool, flowing thence to anodes and, therefore, providing a path for electrons making the current flow in one direction only. The current enters through various anodes in turn, but it passes through the constituting + ve pool of distribution.

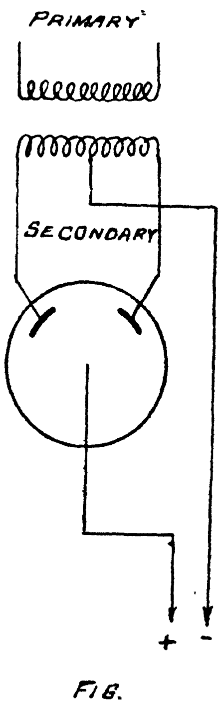
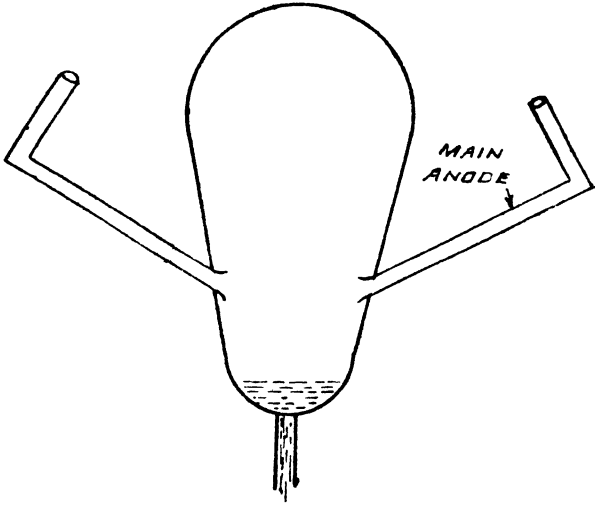


Fig. 5·13.



Fig, 5·14.

259. Metal-Cased Rectifiers:—These are used for large outputs and high voltages, because large volumes of mercury vapour are concerned ; the state of the vacuum must be continuously determinable by vacuum gauges, periodic inspection and renewal of the anodes are necessary. The cylinder is usually of steel, closed by a top anode plate which supports the main and excitation anode and the condensing chamber. The cathode consists of a pool of mercury from which the arc rises through arc funnels and anode shields. The casing and condensing chambers are cooled by water jacket. The main anodes of special steel are insulated by porcelain bushings. Ignition (*i.e.*, preliminary striking of the arc to initiate electronic emission) is accomplished by means of a plunger, maintained a short distance above the cathode surface on a rod depending on the top of the condensing chamber, and capable of being lowered momentarily by the energising of a solenoid. Excitation anodes are connected to a dead load sufficient to maintain the arc when the main load

falls below a critical value. The vacuum is maintained continuously or intermittently by a vacuum pump. Since it is usual to earth the negative side of a D. C. system, the rectifier must be insulated as a whole from earth and the cooling-water connections made by long rubber pipes—Fig. 5·15.

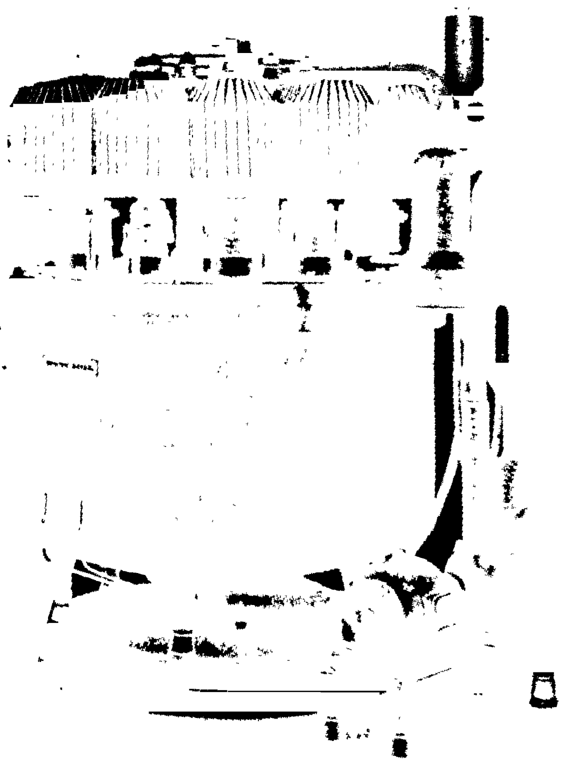


Fig. 5·15.
Metal-clad Mercury Brown Boveri Arc Rectifier.

260. Operating Features:—Parallel operation is governed by the same principles as with D. C. generators, but no reversal of power-flow is possible. The operation is independent of frequency fluctuation, so that rectifiers can safely be run in parallel from separate unconnected A. C. systems, without need of synchronisation. Automatic control is more easily applied to rectifiers than to rotary machinery. Rectifiers can be worked in parallel with converters or batteries.

A mercury rectifier will operate satisfactorily in parallel with other rectifiers, rotary converters or A. C. generators, provided that the voltage load curves of the equipments to be paralleled are closely similar throughout the range of loads to be carried. A new rectifier should be warmed up and its voltage adjusted on an artificial load directly the arc has been struck. But a well-seasoned rectifier, which has been standing idle for not more than a few hours, can be so placed on load.

261. Constructional Features:—The fundamental requirements are—

(1) The striking and maintenance of the arc.

(2) Keeping the anodes and the rectifier chamber at a comparatively low temperature.

(3) The prevention of "back firing" between the anodes and cathode and of flash-over between anodes.

(4) Maintaining sufficient vacuum in the rectifier chamber.

In the beginning the arc is struck by auxiliary means and then the arc is maintained by the current flowing through the rectifier. In the plyphase rectifier, the arc may be regarded as a current conductor, which, pivoted on the cathode, swings from one anode to the next as the potential changes. In the case of glass-bulb rectifiers a side tube *H* (Fig. 5·10) contains mercury which acts as the arc strikes anode. This is connected through a resistance to one of the main anodes. The arc is struck at first by tilting or by an electro-magnetic device until the mercury in *C* is in contact with that in *H*. The bulb is then released and an arc is struck as the mercury separates. This arc is taken up by one of the main anodes if

the direction of the flow of current is correct. If not, the striking operation has to be repeated.

262. Auxiliary Anodes :—In a rectifier, if, for any reason, the current falls below the critical value of about 5 amperes, even for $\frac{1}{1,000,000}$ sec. the main arc goes out. In such cases, to avoid the re-striking of the arc, auxiliary anodes may be used as at D and E, Fig. 5'10. These are connected through special choking coil to an auxiliary secondary winding S, on the transformer. The function of GM is to prevent the current from the auxiliary anodes ever falling the extinction point, and for medium-sized rectifiers the power consumption is about 100 W. In such a case the arc-striking anode H is connected through a resistance to one of the auxiliary anodes instead of to a main anode.

A complete installation of a pair of rectifiers is shown in the diagram 5'17.

Outstanding Features of Converters

263. Static Transformer :—Very high efficiency, simplicity and cost are in its favour ; so this is so much used in sub-stations.

Mercury rectifier stands next to static transformers—next in order are transverters, motor converters and rotary converters. Transverter is suitable for extra high-voltage D. C.

Rotary converters and mercury rectifiers are used in lighting power and traction services, and the high momentary overload capacity and the maintained high efficiency of the rectifier on overloads are specially important advantages in such service. The cost will be the deciding factor for final selection between the two.

The motor converter is intermediate in efficiency between rotary converters and motor generators.

Motor generator is the least efficient of all, at least in the smaller sizes. The initial cost is also greater. These have very great stability of operation ; there is ease of

varying the A. C./D. C. voltage ratio by altering the generator field excitation and great ease of power factor correction, if a synchronous motor is used in the site. This advantage more than compensates the loss in efficiency and higher first cost.

The automatic gear required by mercury rectifiers is smaller than that of rotary converters and the foundation for rectifiers is very little.

264. Applications :—The rectifier can be widely applied, but has naturally been found pre-eminently suitable for loads undergoing considerable fluctuations, such as tramways and railways. The absence of inertia enables any load within the rating to be supplied as demanded. The traction field is, at present, the widest, after which come power and light, rolling mills and electro-chemistry. The rectifier is definitely out of the experimental stage, and, by reason of its high efficiency, is becoming a serious rivel to be synchronous converter. Its limitations in size have as yet scarcely been approached. Already currents up to 20,000 amperes and voltages up to 16,000 volts have been obtained in single units.

The **advantages** of the rectifier may be summarised as follows :—

1. The efficiency high at all loads, can carry momentary overloads.
2. Little auxiliary apparatus is needed.
3. Wear and tear is small and is noiseless.
4. Synchronisation is unnecessary and operates at any frequency.
5. Little floor space is needed and the sets require no solid foundations.

The **disadvantages** are .—

1. Ripples in the rectified wave form are objectionable in some services.
2. Larger transformers than for converting machines are required.
3. No control of the power factor is available.
4. Reversibility is impossible.

265. Synchronous Converter *versus* **Rectifiers:**—A converter gives a direct E. M. F. of constant and uniform value and the latter gives a pulsating and unidirectional voltage and current. In the former the energy is stored in the form of magnetism for an instant, but in the latter there is no magnetic field and no storage of energy. A rectifier will not work on an inductive D. C. circuit but a converter will.

General Instructions for the Installation of Glass Bulb Mercury Rectifiers

266. Unpacking and Erecting a New Rectifier:—After the box is opened the packing material is removed and it is ascertained that the screws holding the bulb in its case are intact. The bulb is shipped in a strong special case which is provided with wire gauze windows so that the fragile nature of the contents can be seen. The case must, on no account, be jolted or tilted out of the vertical position. It is carried in a sling, which is kept in position in the centre of the packing case by means of spring straps screwed to the sides. In order that the heavy mercury may not damage the eloctrodes the bulb is shipped upside down, the mercury being in the condensing chamber.

The top of the bulb packing case is screwed by means of wood screws and is easily removed, so that the condition of the contents can be easily noted. Care should be taken to lift the lid clear of the bulb and should not be allowed to rest on the top of the box.

To withdraw the bulb from its sling, the top springs are released and the coller around the arm of the bulb is unfastened. There is considerable tension on the springs and in order to release them, place the left hand on the body of the bulb and push the bulb towards the spring which is being released, that is, one immediately opposite. This releases the tension and the spring can at the same time be unhooked by the right hand. Cathode legs are not to be pushed; neither the stems, but only the body should be pushed, if necessary. After the springs have been released and the collar removed, the bulb is

ready to be lifted. Take hold of two of the large anode arms on opposite sides of the body and lift the bulb from its box.

When the bulb is clear of the box and still in the upside down position in which it rests in the sling, place the left hand under the large condensing chamber, at the same time holding one arm of the bulb with the right hand, turn the bulb gently allowing the mercury to trickle slowly down the side at which the small exciting anodes are fixed, and directly between these anodes until it falls directly in the cathode chamber at the bottom. Care should be taken not to allow the mercury to fall violently into any of the cathode arms.

No heavy foundation is required, but the cubicles are placed on either channel irons or on a level floor. The bulb is mounted in a cradle in the centre of the bulb chamber and before putting up the bulb the cradle should be inspected to see that it has not been loosened in transit and that all screws are tight. After the bulb has been removed from the case and made into upright position, open the top strap and place the cathode of the bulb into the bottom ring of the cradle, holding it in the upright position with exciting electrodes pointing towards the cradle support. Insert an asbestos packing strip and fasten the top flexible strap around the larger part of the condensing chamber using both hands. The asbestos strip is to prevent the iron strap coming in contact with the glass.

Loosen the clip connector tightening screws carefully over the bulb caps, taking care that the connections are correctly made; connect clips leading to the terminals AE_1 and AE_3, Fig. 5·18, to exciter anodes. Connect main anodes to adjacent anode clips which are fitted at the top of the bulb chamber. Do not rotate the clips when fixing on the bulb, as they may loosen the caps. Hold the clips tight with one hand and tighten the screws with the other, using no tools and without employing greater force. Care should be taken that the clip connections do not affect the bulb in its tilting action (ignition action) ; and when the bulb is connected up, tilt it with hand to see that

it remains freely, and that the clips or clip leads do not come in contact with any metallic part of the cradle or bulb chamber.

Normal Position of Bulb in Cradle :—Connections between the mercury at the cathode and the starting electrodes should only be made when the bulb is in the tilted position, and should be broken when the bulb returns to its normal upright position after tilting. In bulbs having liquid mercury starting electrodes a glass bridge separates the mercury in different pools and the two mercury pools should only make contact when the bulb is tilted. If contact is not broken, the fault may be due to the bulb not coming to rest in the vertical position, in which case the necessary adjustment may be made of the tilting gear. The adjustment should only be that which is necessary to bring the bulb to a true vertical position when at rest.

Effect of Excess of Mercury :—All the bulbs have a small excess of mercury to compensate for the vaporisation which takes place when the bulb is on load. The vaporised mercury condenses in the condensing chamber and much of it falls back again to the mercury cathode. A certain portion, however, remains on the walls of the bulb and the column of mercury at the cathode is, therefore, reduced If, at first starting, the bulb contact is not broken, even after the readjustment of the tilting gear, the bulb should be tilted by hand in the first case and allowed to run on load for about half an hour, when it will be found that it can be started in the usual manner, due to the amount of mercury which has been condensed on the walls of the bulb.

267. The Starting Arrangement at Ormiston :—It is based on the tilting method shown hereafter in the simplified wiring of the " Tilting Method of Starting."

The function of the bulb exciting circuit is to maintain the cathode at an electron emitting temperature on very light loads. The circuit forms a complete single-phase rectifier within the bulb and commences to operate automatically, immediately the main A. C. switch is closed.

Referring to Fig. 5·18 the exciting anodes AE_1 and AE_3 are connected through choke coils to a separate winding on the 3-phase regulating auto-transformer, whilst the cathode of the bulb is joined to the middle point of the winding. The normal voltages at the terminals on open circuit should be AE_1 to AE_3—120 volts AE_1 to AE_2... 60 volts and AE_3 to AE_2...60 volts and when the bulb strikes up in a normal manner, the approximate voltages may be AE_1 to AE_3...*55 volts* AE_1 to AE_2 ...*35 volts* and AE_3 to AE_2 ...*35 volts.*

With normal operation the voltage drop in each of the exciter choke coils, that is, from F_1 to S_1 and from F_3 to S_3, is approximately 50 volts. These voltages are dependent upon the amount of current passing through the circuit and are, therefore, approximate only, but between AE_1 to E_2 and between AE_3 to E_2 the pressure should be the same, so also should be voltage drop across each of the choke coils be equal. The normal current passing through the circuit depends upon the type of the bulb, and it conforms with the following table of values:—

Size of Bulb.	D. C. Exciter Current.
250 amps. ...	6 to 7 amps.
150 to 200 " ...	5½ to 6 "
40 to 100 " ...	5 to 5½ "
20 to 100 " ..	4 to 4½ "

The current adjustment may be made by varying the amount of packing in the magnetic circuit of the choke coils. To obtain the requisite amount of current sometime the choke coil connections are reversed, *e.g.*, E_1 from S_1 to F'_1 and AE_1 from F_1 to S_1. All choke coil clamps are made quite tight fit to avoid inaccuracy of reading on the ammeter, the vibration and hum. Sometimes after 100 hours' service an adjustment is necessary owing to the increase in the internal resistance of the bulb.

Periodic check is necessary and the current is kept up to its maximum allowable value for the type of the bulb as otherwise the bulb will keep dropping out probably on light loads, causing heavy kicks in the voltage, objectionable flickers and lastly a shortening of life of the bulb due to the continual tilting operation taking place in an endeavour to keep the line above. If after adjustment of the current the bulb still drops out, it can be somewhat reconditioned by placing it in a spare set and running for a period of 2 or 3 weeks on exciter current only, after which treatment the bulb will be fit for further service.

268. Striking Up the Bulb:—By mounting the bulb in a cradle free to oscillate about a fixed fulcrum, the ignition electrode *IE* is brought into contact with the mercury cathode pool *C*. This action is made entirely automatic at Ormiston. *IE* is made alive before and during the tilting operation, but is cut out of service immediately the bulb has struck up. *IE* is connected through a relay coil in automatic type to terminal E_3 of the exciter winding and after the contact between *IE* and *C* is complete the bulb returns to the vertical position by gravity and this breaks the circuit between *IE* and *C*, causing an arc to be drawn out between them which ionises the mercury vapour in the bulb and thereby enables the exciting electrodes to function.

A cold bulb may require tilting operations to cause sufficient vapour pressure to enable the exciting electrodes to pass current through the circuit. Normal vacuum is about ·045 mm. of mercury pressure at about 70°*C*. If the vacuum is poor, the H_g will form a heavy mirror on the walls of the bulb immediately an attempt is made to strike up, and mercury will assume a dirty appearance. In this event the bulb is unfit for further service. If mirror effect is slight, the bulb should be left to operate on exciter circuit only for a few hours, by which time its condition will have become normal, provided there is no break in the glass or no faulty seals round the electrode caps.

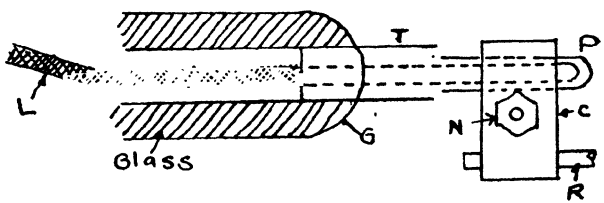
Assuming correct voltage at the exciter electrode terminal, if arc is drawn out between *IE* and *C* upon tilting the bulb, but after repeated efforts the bulb fails

to strike up, then the vacuum is defective. If, on tilting by hand, it is found that the mercury falls back slowly into the chamber instead of emitting a sharp metallic click, then the vacuum is supposed to be poor. Referring to Fig. 5·18 the sequence of starting operations (automatic) is as follows:—The exciter winding is charged up immediately the pressure is impressed upon the main regulating auto-transformer. The circuit is then made from E_3 through E_3F to the two contacts on the D. C. relay. From one of these contacts a lead is taken to the A. C. relay coil and thence through 10 amps. fuse to *IE*, whilst from the other contact a lead is taken to a contact on the A. C. relay, thence to the tilting relay operating solenoid and so through another 10 amps. fuse to E_1. This energises the tilting relay solenoid, causing it by the action of the magnetic rocker to tilt the bulb cradle, while at the same time the A. C. relay coil and the ignition electrode *IE* are energised, causing the contacts of the A. C. relay to open to de-energise the tilting relay, and so inaugurate an oscillatory motion to the bulb-cradle. If all is normal, the ignition arc is drawn out and current will then flow *via* the mercury vapour within the bulb from E_3 through the exciter choke coils to the cathode pool *C* through the D. C. relay coil to the middle point of the exciter winding at E_2. This will then energise the D. C. relay coil, which will open its contacts to cut off the supply, the A. C. relay coil and also the tilting relay solenoid.

269. Fan:—The fan motor is 3-phase squirrel-cage type. It is fed from an entirely separate winding on each leg of the main regulating auto-transformer and has a working voltage of about 50. The wooden blades give a good result.

The fan is a very important piece of apparatus, for if it failed to function for any length of time on peak load, the bulb would "flash over," *i.e.*, cease to function as a one-way valve and give a reversal of flow of current sufficient probably to damage the bulb. The fuses in the main anode circuit generally protect the bulb.

270. Seal :—The seal in the case of glass-bulb rectifier is most carefully designed, not so much from the view-point of providing a light joint, although that is essential, so as to prevent cracking due to unequal expansion. Several devices are employed for this, one of which, that can carry 200 to 600 amperes, is described. Referring to Fig. 5·19 it represents the leading-in wire, and *P*, a platinum tube, slipped over the rod and welded to it. The glass vessel *G* is moulded on to the platinum sleeve with glass-metal joint at *P*. Glass and platinum having approximately the same coefficient of expansion, the joint *P* is unaffected by the heat from the bulb, or that conducted from the leading in wire. *T* is a platinum thimble to which the glass joint *G* is made, the main connection is made of large standard copper wire soldered solid at the end and is carried into the thimble to the point *P*. A clamp *C* is then put over the thimble and into it is inserted the main filament lead and support *R*. On tightening the nut and bolt *N* the thimble is squeezed until good electrical contact is made. The electrical connection is insured through the wall of the tube which expands only in a longitudinal direction with lead and do not, in any way, tend to crack the glass seal.



Glass Seal for Very High Currents

Fig. 5·19.

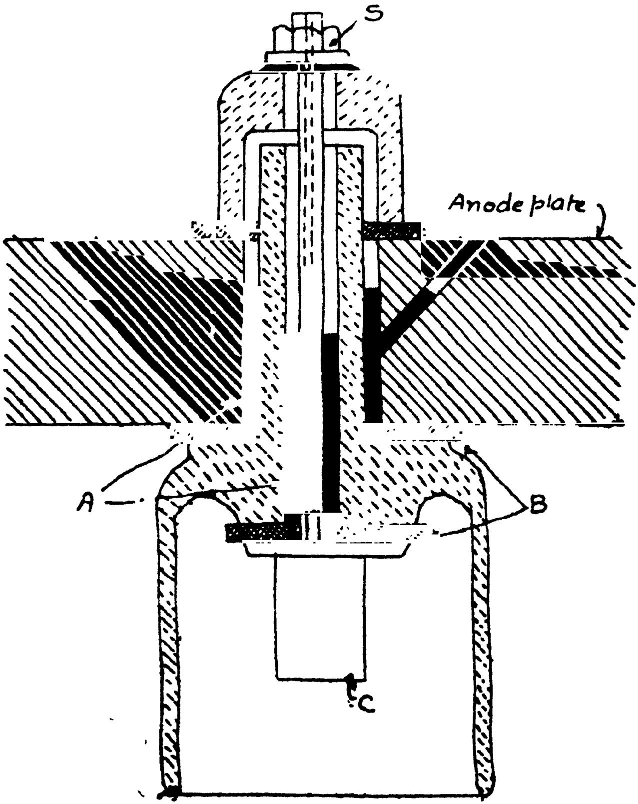


Fig 5·20.

The sketch illustrates here a typical seal employing mercury and asbestos packing. The impregnation of asbestos washer SB, which clamps the anode insulator in position by mercury when the vacuum is applied, is employed

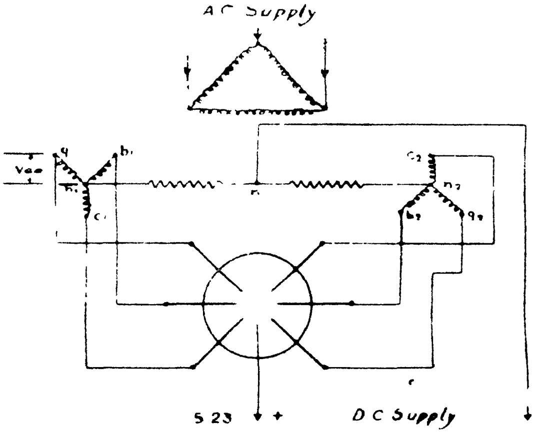


Fig. 5·23

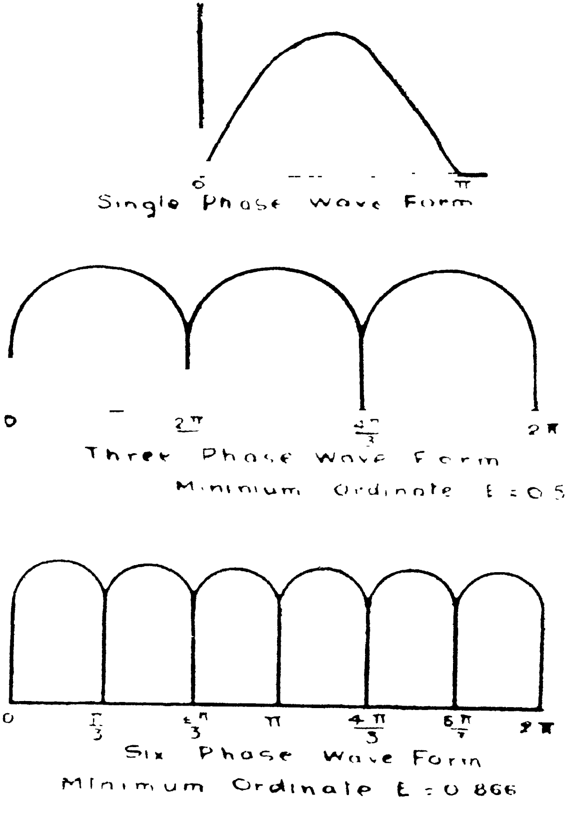

Single Phase Wave Form
Three Phase Wave Form
Minimium Ordinate E = 0 5
Six Phase Wave Form
Minimum Ordinate E = 0 866

Fig. 5·22

Fig. 5·21

Mercury Arc Rectifier Circuit.

271. Connection :—Comparative features of wave forms, Fig. 5'22, obtained with a single-phase, 3-phase and 6-phase rectification, are given. It also illustrates the superiority of 6-phase rectification over other systems.

To obtain the best performances from the point of view of D. C. wave form and power factor, six-phase operation is generally provided. As in the case of 3-phase equipments, the method of connections is as shown in Fig. 5'23. A special transformer is then employed between the neutral points of the secondary winding which has the effect of always maintaining two anodes in service at one time.

In Fig. 5'21 :—

1. Bulb.
7. Std. Relay and Resistance.
10. Main A. C. Fuses.
16. Auxiliary Fuses E_1, E_2, E_3, and S_1, S_2, S_3.
18. Spark Gap of Arrester.
19. Cathode Silt Resistance.
24. D. C Knife Switch.
33. Bulb-starting Coil.
34. Std. Exciter Anode Inductance.
37. Compensating Cathode Inductance.
38. Std. S. Limb Anode Choke.
44. Cathode Insulators.
45. Anode Insulator.

Fig. 5'21 shows a simple diagram of a mercury arc reçtifier sub-station. Only the main connections are shown in this diagram.

272. The operation is as follows :—When anode a_1 is operating, the current flows along coil n_1n.—Fig. 5 23. This energises the core of the inter-phase transformer including a voltage on coil nn_2, which, added to the potential of anode c_2, brings the latter up to the value of a_1 during the first part of the operation of c_2. In this way, you obtain a full voltage in the secondary side and the voltage of each anode to the mid-point of the transformer secondary which forms the +ve-pole on the D. C. system being of course half that value.

In the same way during the second period of the operation of anode c_2, anode b_1 is brought into service. As a result of the above, each anode is in service for a third of a cycle and consequently the anode current per phase corresponding to the D. C. I, flowing through the cathode of the bulb is $\frac{1}{2\sqrt{3}}$.

To obtain the secondary voltage of a transformer ($V_{a.c}$) on a 3-phase supply to feed a rectifier to give any D. C. voltage output ($V_{d.c.}$) the following formula is employed :— $V_{a.c.} = \frac{V_{d.c.}+20}{\cdot 678}$, where $V_{d.c.}$ = D. C. voltage at low load, 20 is the voltage drop across the bulb arc and ·678 is a factor applicable for 3-phase supply, where the transformer is wound 3-phase or 6-phase. The factor for single-phase is 0·46. The over-all efficiency of the equipments remains very high at low loads.

273. Efficiency :—The table gives representative efficiency figures for rectifier equipment. They are not appreciably affected by the size of the plant within wide limits. It will be noted that the over-all efficiency increases with the D. C. voltage output, this being due to the fact that the voltage drop across the arc in any case is constant.

Efficiency Table of Hewettic Rectifier at Various D. C. Volts.

Load.	D. C. voltage output 550/600	D. C. voltage output 400/460	D. C. voltage output 200/250	D. C. voltage output 100/130
$\frac{5}{4}$	93 %	92·5 %	86·5 %	80·0 %
$\frac{4}{4}$	93·5 %	93 %	87 %	81 %
$\frac{3}{4}$	93·7 %	93 %	87 %	82 %
$\frac{2}{4}$	93 %	92 %	86 %	81 %
$\frac{1}{4}$	91 %	90 %	84 %	79 %

274. Circuit:—The most important relays and the method of connecting them up are shown for a single bulb with six arms in Fig. 5·21 No separate explanation is given as the important principles and functions of each part have been considered already.

275. Grouping:—Bulbs may be grouped and fed by one transformer wound with a number of independent secondary windings corresponding to the number of bulbs.

The most common arrangement is of two bulbs fed by one transformer, the two bulbs being supplied by the two independent three-phase component windings which make up the six-phase secondary. The stability

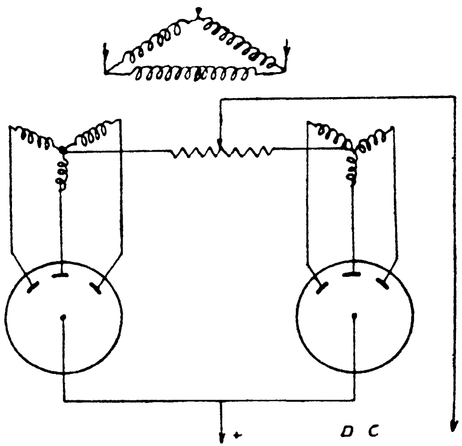


Fig. 5·22.

in running and proper distribution of the load is ensured by the shunt and the drooping characteristic of each of the rectifier units in parallel, regarding each unit as the bulb and its respective component of the secondary winding of the transformer.

The method just described is one almost always employed in multi-bulb Rectifier Bank, and if the number of bulbs is two and the transformer is wound for 6 or

12-phase or if the number of bulbs is four, and the transformer is wound for 12-phase, no further means are necessary to ensure correct load distribution between the bulbs.

However, it is equally possible to obtain load distribution between a number of bulbs connected directly to

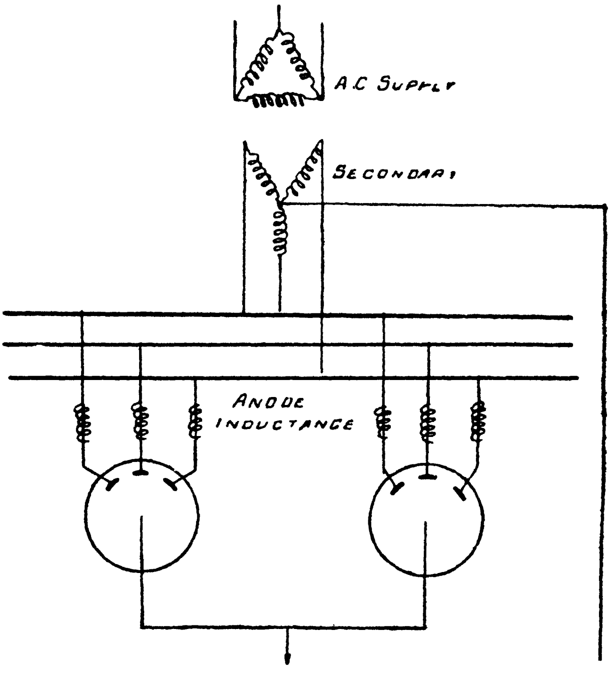


Fig. 5·23.

the same common transformer winding. One method is the employment of a set of anode inductance coils per bulb which have the effect of converting the characteristic of each bulb to a drooping type (Fig. 5·23). The more usual method, however, is the employment of compensating transformer.

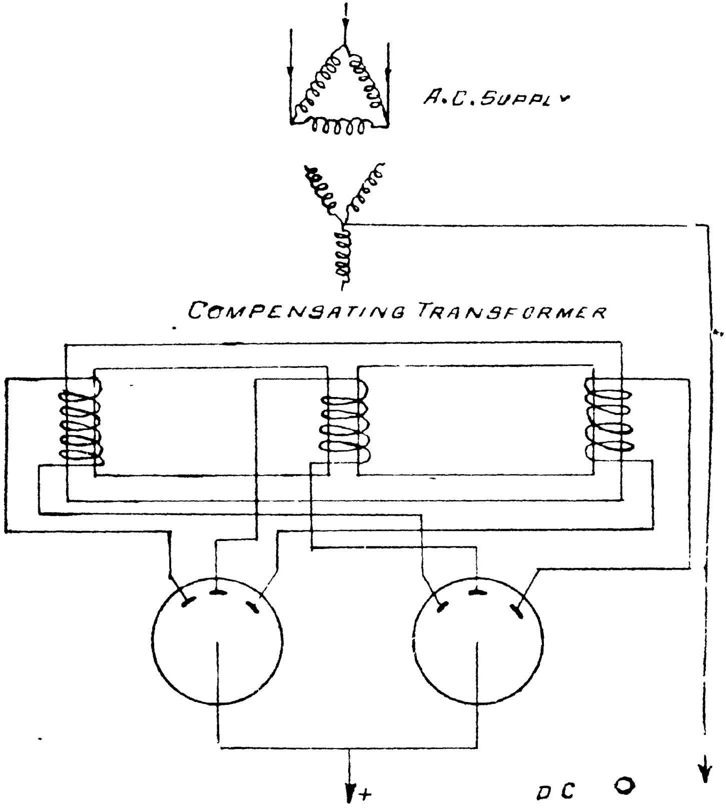


Fig. 5·27.

Their power factor is as follows :—

6-phase connected	equipments	... 0·94
3-phase connected	,,	... 0·95
Single-phase connected	,,	... 0·87

These are made up of two sets of similar coils wound in opposition on a common core (Fig. 5·27) through which is arranged to pass the current into each of the two bulbs, which is required to balance together.

As long as the currents in both sections are equal, no appreciable voltage is induced in the windings and the fluxes in the core are equal and opposite. If, however, a change occurs in the current output of the bulbs and, therefore, in out-set of coils without a corresponding change in the other bulb and set of coils, the fluxes obtained cause a drop in the voltage in the winding carrying more current, thereby inducing the other bulb to pick up more and take an equal load so that conditions of equilibrium are again established. These compensating transformers are very frequently employed, not only to ensure an even distribution of load, between two or more bulbs in parallel, but also between two groups of three arms each in a 6-arm bulb connected three-phase Compensating transformers in contrast with anode inductance do not increase the inherent regulation of the rectifier bank as a whole and this is why they are often preferred.

276. Three-Wire Balancing :—If it is desired to deal with the out of balance loads on a 3-wire system, then rectifier bulbs may be connected in series, one to feed each side of the mid-wire. With two bulbs feeding a 3-wire network in this way and without any addition of voltage regulating gear, the voltage balance on both sides will be maintained with an out of balance of as much as 25 % of the current outputs of the bulbs (Fig. 5·28). The bulbs, however, would be capable of dealing with higher amounts of out of balance with a corresponding higher voltage difference. By running rectifiers in this way, the bulbs operate at a lower voltage than if connected across outers, that is to say, for instance, in a 400/200 volts 3-wire system, the bulbs would each be delivering 200 volts. Therefore, if it is desired to increase the capacity of such an installation, the efficiency is increased by arranging extra bulb to feed across the outers at 400 volts leaving the out of balance load to be dealt with by the first two.

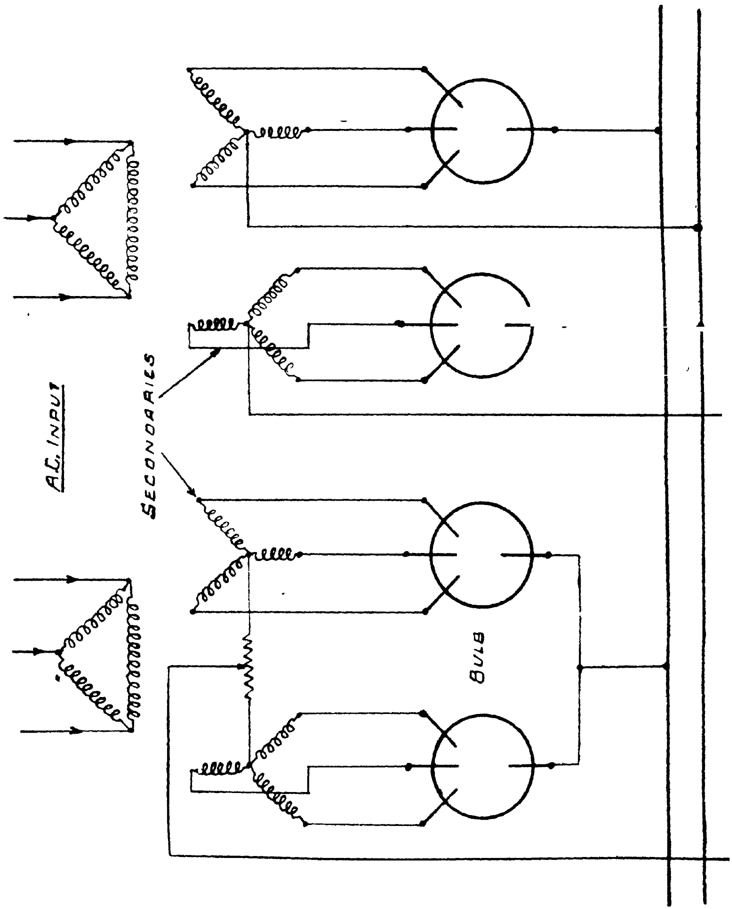


Fig. 5·28.
Three-Wire Balancing.

Three-wire Balancing.

Overload rating °/o.	Time of overload in minute.
16 ...	60
25 ...	30
45 ...	20
50 ...	17
70 ...	10
100 ...	5

In these ways banks of rectifier bulbs can be arranged with any number of bulbs as there are many banks in service with 2, 4, 6, 8, 16 and 20 bulbs.

D. C. Voltage Control :—A rectifier equipment is similar to a static transformer as regards voltage control, that is to say, it has an inherent drooping characteristic and voltage adjustment available only on off-load by means of tappings on the primary side of the transformer.

The arrangement on Hewittic Rectifiers in BEST SUB-STATIONS is of the "Inductance Regulator" type, which is automatic in action. This operates when the voltage drops down by the operation of a relay which starts a motor. This motor moves the regulator and thus adjusts the primary voltage.

277. Auto-Reclose Switch :—This switch forms an important part of the switchgear, as there is no attendant.

278. Protection :—Fig. 5·29 gives a device for the protection of a rectifier when it is in parallel with automatic rotary converter. In case E. H. T. supply totally fails, the latter is locked out. When the E. H. T. supply is restored, there is a chance of the rectifier taking up the whole load taken by the rotary converter and damaging the whole plant (rectifier) if the protective apparatus fails to act. To prevent this, a contactor is used which opens the circuit of the inter-connector direct-current feeder, so that the rectifier sub-station supplies its own network

only and parallels itself automatically, only if, and when, the rotary converter is feeding into its network at the correct voltage.

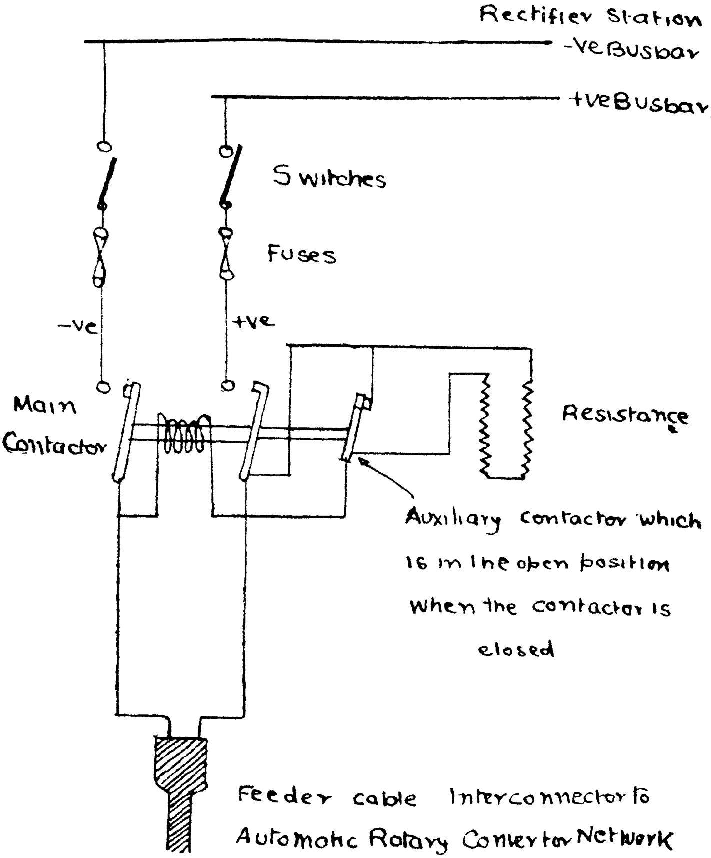


Fig. 5·29.

279. Bulb-Tilting Mechanism :—The whole tilting mechanism is mounted on a cast-iron base, bolted to the back panel of the bulb chamber, the action being shown in explanation in Fig. 5 30. The motion comprises a solenoid *C.T.* controlling a plunger *P* which is coupled to a lever *A*, rotating loose on ball bearing spindle *O*. Lever *A* drives lever *B* through coiled spring *S*, the pins *F* and *E* engaging the spring as shown. *E* is secured to the spindle and carries a balance weight *W*, the position of the weight on *B* being adjustable to suit the type of bulb. Lever *C* is secured to the spindle, the bulb support being clamped to this lever.

When the solenoid is energised, the plunger *P* is drawn up, the bulb is tilted and the shock is prevented by the spring. The throw of the plunger is controlled by the stop screw *O*, and *C* can be adjusted by slackening its set screw and rotating it on the spindle until the bulb is in the correct vertical position and all screws thoroughly tightened before it is replaced.

The correct position of the bulb in the support and of the support with reference to the tilting motion is shown in Fig. 5·30. The solenoid is connected through.

(*a*) A. C. and D. C. relay contacts and fuse FE_3 to terminal E_3 of exciter transformers.

(*b*) FE_1 to terminal E_1. The normal voltage EI to E_3 is 120.

280. Hand-Tilting Motion :—A cast-iron frame is bolted to the back of the bulb chamber, and is provided with bearings for spindle *O*, to which is securely clamped the lever *C*, the normal position of bulb in the support, and of support with reference to the spindle. Adjustable stop screws, S_1 and S_2, control the operation position of the bulb and angle of the tilt for starting up, tilting being affected by means of hand wheel, which projects from the back of the bulb chamber to the front of the cubicle. The position of the balance weight *W* can be varied to suit the type of bulb.

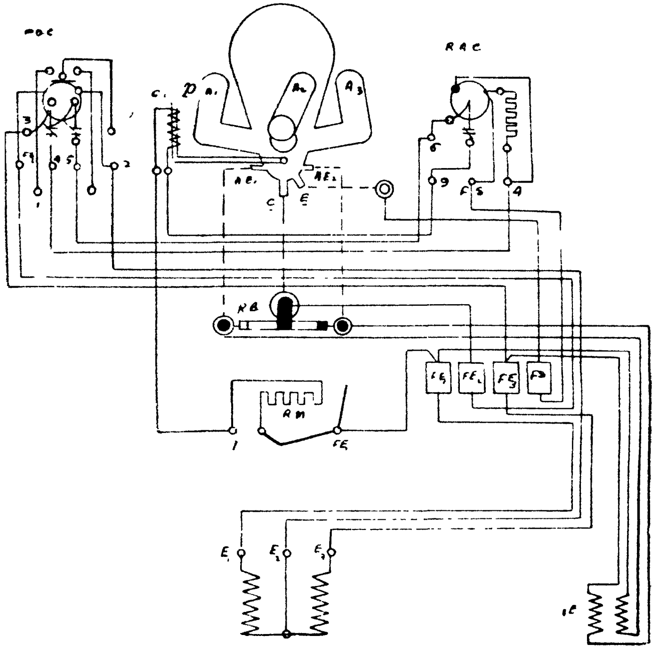


Fig. 5·31.
Standard Diagram of Connection for Tilting and Starting Circuits

281. In Fig. 5·31 :—

A **1, 2, 3** Main Anode Electrode.
A E **1** & **2** Exciter Anode Electrode.
B Bulb.
C Main Electrode.
C T Tilting Coil.
E Starting Electrode.
E W Exciter of Starting Winding on Transformer.
F E **1, 2, 3** Exciter Winding Fuses.
Fs Starting Fuse.
I E Exciter Inductance.
R A C & *R D C* Starting Relay.
R B Resistance,
R M Thermostatic Cut-out Relay.

282. Operation of Automatic Bulb-Tilting Motion :—As given in the Fig. 5·31 the operating equipment consists of A. C. relay (*R. A. C.*), D. C. Relay (*R. D. C.*) and tilting solenoid (*C. T.*). The solenoid *C. T.* is fitted to the back panel of the bulb chamber—the relays being fixed to the outside of this panel and facing the front of the rectifier cubicle. Doors are provided to the cubicle to give access to the relays, and to the fuses controlling the different circuits There are three circuits all of which are operated from a single-phase transformer or from a single-phase winding on the main or regulating transformer of the rectifier

The circuits are (1) tilting circuit ; (2) ignition or starting circuit ; (3) circuit excitation.

(1) The tilting circuit is controlled by relays *R. A. C.* and also by *R. D. C.* The tilting solenoid is energised, the bulb tilting and starting anode comes into contact with mercury, thereby closing the ignition circuit.

(2) The A. C. relay contacts are opened by the circuit through the A. C. relay coil and No. 1 circuit is broken.

The bulb then drops back due to gravity to its normal vertical position, contacts between *S* and the mercury is broken and a small arc is formed which vaporises the mercury and the bulb ignites on the exciting circuit.

The A. C. relay contacts close immediately the contact is broken between *S* and the mercury, and the bulb does not ignite on the first tilt, the tilting operation is continued until the circuit is broken by the retarding up of the excitation circuit, and operation of the D. C. relay.

(3) The D. C. relay contacts are broken and opened by the current flowing through the coil, thereby breaking both Nos. (1) and (2) circuits. Should the bulb drop out due to low current in No. (3) circuit, the D. C. relay contacts close and the tilting operation is repeated.

If the circuits fail to operate, inspect all the fuses, and tighten up, when necessary, clean relay contacts, if required, and ascertain if there is a good circuit through

the flexible leads connecting the relay contacts to the terminals.

283. General Instructions for Working in Rectifier Bulbs:—When possible, the rectifier cubicles should be tried out in the first case with test bulbs. The excitation circuit should be adjusted in the first case on three bulbs, which should then be put on light load, to make sure that all circuits are correct. After trying out the cubicles on test bulbs, the actual service bulbs can then be started up as follows:—

Excitation circuits must be adjusted to correct value for the type of bulb. If the adjustment has been made in the first case on a test bulb, the ammeter should be kept in circuit for the service bulb, since its terminal resistance may not be the same as that of the test bulb and re-adjustment may then be required.

The service bulbs must be allowed to operate without fans on their correctly adjusted excitation circuit for $\frac{1}{2}$ hour to prepare them for load. The load should be applied gradually when starting the bulb for the first time.

Bulbs must not be operated beyond their rated capacity, since excessive current will shorten their life. Bulb clips should be inspected at regular intervals and lightened up, where necessary. As already stated. the clips, on no account, be rotated when in position on the caps and no great force must be used when tightening them.

All rectifier bulbs gradually blacken when in continual use. The blackening does not indicate any defect as they may operate in this condition for thousands of hours, but it reduces the amount of mercury at the cathode. In this event some readjustment of the bulb-tilting motion may be required to ensure contact between mercury and shorting anode, when the bulb is tilted to start.

As the internal resistance of the new bulb changes after the first 100 hours of life or so, the current taken by the exciter should be checked, and it will usually be found to have decreased, in which event it must again be brought up to its maximum value.

When the excitation current is too low, the bulb frequency drops out, more especially when cold, and as frequent tilting is not good for the bulb, this fault should be remedied without delay.

Other Types of Rectifiers

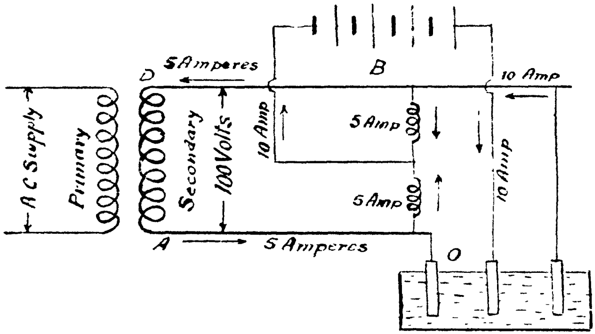


Fig. 5 32.

284. Electrolytic Rectifier:—We have just seen the selection of current in the mercury vapour arc rectifier. This phenomenon of selection of current is also seen in the case of many metals, which, when immersed in some solution, offer a high resistance to a flow of current when it is flowing from the metal to the solution, but very low resistance when a current flows from the liquid to the metal. Again, for similar reason, when a plate of aluminium and a plate of lead, carbon or steel are

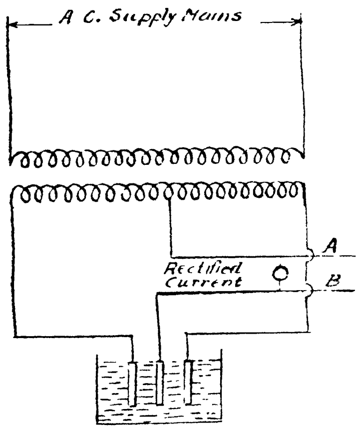


Fig. 5·33.

placed in an electrolyte, a current will pass from the lead to the aluminium plate, but hardly any current will flow in the reverse direction. Hence, the current flowing between the terminals *A* and *B*, Figs. 5·32 and 5·33, will be unidirectional but pulsating. This last combination serves as an electric valve and both the electrolytic rectifier and the lightning arresters are based upon this principle.

The electrolyte may be neutral ammonium sulphate, ammonium phosphate or sodium borate dissolved in water.

Efficiency for battery charging is about 30 per cent., if the temperature is not more than 30° *C* and seldom exceeds 60 per cent. The efficiency increases with decrease in the amount of the current to be rectified. The size one ampere requires 2 sq. inches of aluminium and lead plate also of the same size. The strength of current is regulated by a resistance.

Characteristics :—Cheap, simple and requires no sustaining circuit.

Use :—In X-Ray equipments and experimental purposes. It is satisfactory for handing small intermittent loads.

The power factor of the electrolytic rectifiers exceeds 90 °/o according to the dimensions and loading of the rectifiers and the nature of the electrolyte; the efficiency is from 50 to 60 °/o up to from 65 to 75 °/o, about 70 °/o is a reasonable average.

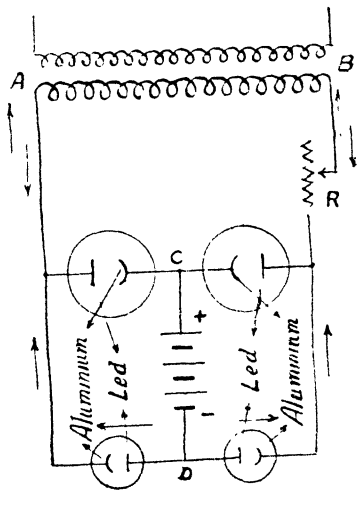


Fig. 5·34.

Care :—For these results the rectifier should be used daily, just as daily "forming" is needed in electrolytic arresters.

Trouble :—Rapid corrosion of the aluminium plates at the surface of the electrolyte.

Remedy :—Keep the electrodes submerged with insulated leading in wires.

285. Nodon Valve :—The underlying principle of the Nodon valve is that the electrolyte of a cell allows only a one way or unidirectional current to pass through it. This can be explained from the Fig. 5·35. Let the four cells be joined in rhombus form, as shown. Let the current be + ve at any instant at the point *A*. The cell No. II allows it to pass while No. I and III do not allow the current to pass through, so this positive current has reached the terminal *C*. Next moment, suppose *A* has —ve current. Now it can pass through —ve electrode only. This means the —ve current passes through No. III and reaches the point *D* because the positive electrodes of II and IV do not allow this current to pass through them. Taking the case of point *B*, we find that the positive charge at any instant would go through the terminal *C*, while —ve current at any instant would go through terminal *D* to No. IV. Thus we find that the terminals *C* and *D* are always having + ve and —ve polarites, no matter of what kind the current is at *A* and *B*. Therefore, by supplying *A*, *C*, from the secondary of a transformer, we get unidirectional current from the terminals *C* and *D*. Hence, a Nodon valve acts as a rectifier.

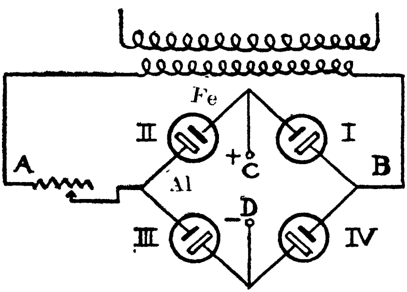


Fig. 5·35.
Electrolytic Rectifiers connected to utilise both half waves of A. C. supply.

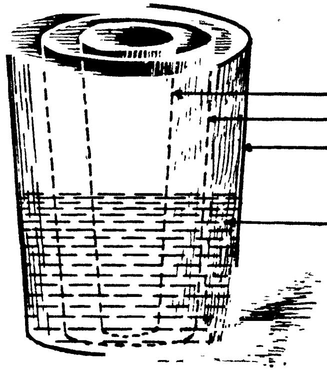


Fig. 5'36.

Construction :—It consists of an iron cylinder or vessel, having lead plate, in which an aluminium cylinder is placed. The solution of ammonium phosphate is used as an electrolyte—Fig. 5'36.

Bridge Circuit :—Note that the bridge circuit in Fig. 5'35 is often used when the output potential required will stress the rectifiers severely. It materially reduces the reversed potential applied to the rectifier units. It is also used for laboratory works when a transformer with mid-tap is not available and is commonly used with copper oxide rectifiers.

286. Half Wave Rectifier :—Sometimes a steady output current is not necessary, such as on charging battery. In many cases a half wave rectification circuit is used containing a single rectifier in circuit and often a current limiting resistance all connected in series and fed from a source of alternating-current power. It is simple, but the wave forms are such that the apparatus is not utilised to the best advantage—Fig. 5'37.

287. Full wave rectification circuits use two rectifiers. Resistance in the load circuit results in a steady output current at the expense of the primary current

wave shape which tends to become rectangular in form. By placing the reactance in the primary an excellent battery charger results, although the output current is discontinuous--Fig. 5·38.

Mechanical Rectifier

288. Vibrating Rectifier:—It rectifies mechanically through an electrically operated vibrating switch or contact that closes at such times in synchronism with the alternations of the current that the current can flow only in one direction. The reversing action is done at the moment when the current-flow is zero.

Efficiency :—About 55 per cent.

Characteristic :—Efficient and inexpensive. It is used in charging three-cell vehicle battery and deliver a current of from 8 to 8·5 amperes.

(2) Mechanical rectifiers of another type consist of a commutator driven by a synchronous motor.

Efficiency :—Poor at light loads.

Note carefully that the current from a rectifier is not suitable for use in an inductive circuit as its pulsations would set up eddy current and cause hysteresis loss. Hence, it cannot be used to excite the field of an alternator, whereas the current from a converter being very steady can be used as direct current.

289. The Oxide Cathode Rectifier :—This is the latest type of static rectifier and is exceedingly simple. Valve used is of the flat cathode gas-filled type and is very robust and dependable In its simplest form it comprises merely a filament of Barium oxide and two anodes of graphite contained in a gas-filled bulb The filament is heated direct by A. C. from a winding on the transformer. When the filament is heated, it emits electrons. In other words, there is flow of electrons from the filament (cathode) to the anodes. Current will flow in opposite direction to the flow of electrons but effectively ; it cannot flow in the same direction as the flow of electrons. Therefore, in practice, a D. C. flow takes place from the anodes to the filament, *i.e.*, current passes through the

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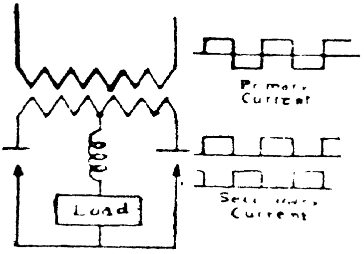

Fig. 5 37

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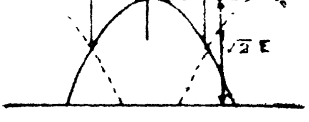


Fig. 5·39

valve in one direction only and, consequently, becomes rectified or made direct current.

The general principle of the oxide cathode rectifier will be more clear from the diagram. A. C. is first transformed by the transformer to a convenient value. It then passes to the valve. Current can flow through this valve in one direction only. It flows alternatively from one side to the other, thence to the load and back to the transformers.

These rectifiers are made in sizes up to 150 amperes at 110 volts only in general and the efficiency is about 82 °/o.

290. Rectifier Harmonic :—The fundamental characteristics of a rectifier are such that the generation of certain harmonics is inherent in the operation. These harmonics can be decreased by increasing the number of secondary phases and can be further controlled by means of resonant shunts. Smoothing reactions can also be used for suppression of ripples in the D. C. output. The harmonics in the input current must be kept below an amount which will cause interference with other apparatus. This will vary with local conditions and may be kept from leaving circuits by means of tuned harmonic shunts.

291. Voltage ratio of circuit with steady output current :—*Vide* Fig. 5·39.

Let P=Number of phases of the rectifier, *i.e.*, P secondaries uniformly distributed in phase and carrying a continuous output current The number of phases P is 2 for the ordinary single-phase "full-wave" rectifiers.

For this circuit really has two secondaries separated by 180 degrees in phase when anode to neutral voltage is considered This relation is obtained by noting that only the anode at highest potential is carrying current and that each anode is at a higher potential than any other for a period of $2\,\pi/P$.

The output voltage is then the average value of the highest portion of a sign wave, the portion taken being from a point π/P before the maximum to a point π/P after it.

V=Output voltage is taken to be the average value of the highest portion of a given wave, taken from a point $\frac{\pi}{P}$ before the maximum to a point $\frac{\pi}{P}$ after t.

$$V=\sqrt{2}\,E\,\frac{P}{\pi}\,sin\,\frac{\pi}{P}$$

E=R. M. S. secondary voltage to neutral.

292. Ripple or Choke Voltage—To obtain a steady output current from the rectifiers requires a steady output voltage, but the potential of the anode which is carrying the current is constantly changing which gives rise to a ripple in the rectified potential. This is absorbed by an inductance which is part of the rectifier circuit. The various components of this ripple are found by harmonic analysis to be

$$A_n = \frac{\pm\sqrt{2}\,V}{(n^2-1)}$$

where A_n is the R. M. S. value of the component with a frequency n times the frequency of the alternating-current source. Only those frequencies for which n is an integral multiple of P are present. Other values given by the equation are fictitious.

293. Power Factor of Rectifier :—If each primary feeds only two secondaries so that it carries two rectangular current waves without overlapping, then its power factor

$$\text{P. F.}=\frac{2\sqrt{P}}{\pi}=sin\,\frac{\pi}{P},$$ where P is the number of secondary windings in each group, *i.e.*, two for single-phase (double-wave) and three for double three-phase or six for six-phase.

Rectangular waves are obtained only when there is no regulation due to reactance, and it will be found that the wattless current consists entirely of harmonics and contains no fundamental frequency component 90 degrees

from the applied voltage. For this reason rectifiers, when operated in parallel with other devices, usually improve the power factor of the entire load as the unity power factor components add directly and the harmonic components do not. Because some of the harmonics can circulate in a closed delta, the power factor of the lines-feeding delta-connected primaries will be better than the power factor of an individual primary.

Rectifiers with regulation due to reactance will have a small, zero power factor. Fundamental frequency component in the input current, for in this case, the current wave is displaced in phase.

Properties of Thermionic (Vacuum Tubes)

294. Thermionic Valves:—There are various apparatus—the application of which ranges from the transmission and reception of 'wireless' signals (*i.e.*, electrical communications), to the control of all manner of circuits and machineries by relay action and high-power services of all kinds—which depend upon the phenomena of emission of electrons (*i.e* , charger of negative electricity) from a heated electrode. If there are two electrodes, one (an anode) kept at a higher potential than the other (a cathode), then the emission of electrons from the hot cathode will, under favourable conditions, maintain a flow of current from anode to cathode. (The convention universally accepted by all, is that the direction of flow anode to cathode, *i.e* , from positive to negative), but the direction of flow for electron (*i.e* , negative electricity) is from cathode to anode, *i.e.*, negative to positive). Now, if the anode be cool, there will be no discharge of electrons from it, and current cannot flow in the direction of cathode to anode. Hence, two such electrodes can be used for rectification. *This action of rectification is lost if the anode gets heated enough to emit electrons.*

If the two electrodes be kept in a vacuum, the current flowing between them will be proportional to the emission of electrons of the hot cathode, but if the space between the electrodes be filled with, say, mercury vapour, the mercury at once gets "ionised" by impact, and both

positive and negative ions are liberated. Thus the conductivity of the path between the two electrodes is much increased.

The original Flaming valve and its many modifications belong to the vacuum class of valves, whilst the mercury rectifiers and the Tungar rectifier belong to the class in which thermionic action is supplemented by ionisation of vapour by impact.

In (high-vacuum) 'hard' valves the current-flow between the electrodes is practically proportional to the emission of electrons from the hot cathode, while in the case of "soft" (low vacuum) valves, the ionised gas or vapour liberates many times more electrons than what is emitted by the hot cathode; the effective resistance being low, these valves can be used for comparatively low voltage. The positive ions liberated by ionisation are attracted to the cathode, the temperature of which is raised by the bombardment of these relatively heavy ions. Heating the cathode by this process is part of the normal operation of a mercury rectifier. The defect is that it shortens the life of the valve in which the cathode is an incandescent filament. Electrons, on the other hand, being many times lighter than positive ions, the bombardment of the anodes by electrons causes comparatively no heating; in case of high-power valves it is sometimes necessary and its artificial arrangements are made to cool the anode.

In general, the efficiency of the ionic valves increases with the increase of anode voltage, because it lowers the percentage value of the voltage drop between anode and cathode. Obviously, it is always economical to increase the power by increasing the voltage rather than current, because,—

(1) the percentage value of internal voltage drop is reduced, and

(2) to increase the current involves more wastage of energy due to heating of the cathode.

Tubes:—A vacuum tube having a plate and a filament anode and cathode, respectively, is known as DIODE VALVE. One containing three things, a cathode (filament), an anode (plate) and a grid is known as a TRIODE VALVE.

One containing a filament, anode and two grids is known as four electrode or TETRODE VALVE. Screen grids in space, change grid tube according to the grid function. The last, with an additional element, is known as five-electrode vacuum tube or PENTODE VALVE.

The discharge of electrons from the cathode is given by the equation—

$$I_s = AT^n \times \epsilon^{-\frac{w}{KT}} \ldots \quad (1).$$

This gives the current in amperes per sq. cm. of filament surface and involves a constant A, the absolute temperature T, the work function w, and the gas constant K

The coefficient A depends upon the material of the filament and upon the number of free electrons per cu. cm. therein, along with some other minor things as well as on the value of "n."

Exponent n is sometimes given as $\frac{1}{2}$ and again as 2. The quantity w is the amount of work done by an electron in moving from the inner portion of the filament to the surface. The quantity K is the gas constant per electron where the electron is treated as if it were a molecule of a perfect gas. Quantity w is sometimes expressed in terms of equivalent volts as given by $w=\phi e$, where ϕ is the equivalent voltage—this when multiplied by the charge e on an electron yields the work function w.

Electron affinity (in volts) ϕ for some important elements is given below :—

Platinum	... 6·27	The value of A	$1·7 \times 10^4$
Tungsten	... 4·52		60·2
Molybdenum	... 4·4		60·2
Carbon	... 3·93		5·93

The Filament (i.e., Cathode), the Source of Electrons :—The filament should have a long type and must emit electrons with minimum expenditure of work (*i.e*, energy). To satisfy these conditions Tungsten is the best for all practical purposes and is used in general. Thoriated-Tungsten oxide coated platinum or nickel alloys are sometimes used for filaments. The trouble lies in the fact that the higher the temperature the

greater the emission and shorter the life of the filament, and hence the selection of the material for the filament must be made after a careful study of the readings from experimental observations of various metals and alloys.

The construction of the cathode and filament should be such that it can be firmly fitted up in place.

It must have maximum possible surface out of the material used and should be so related to other parts that the energy dissipated in it can be radiated and conducted immediately to the surrounding objects, so that the cooling effect at its ends is not appreciable.

The Plate or Anode :—The characteristic of the plate should be (as it has got to receive the emitted electrons from the cathode) the ability to dissipate power $F_p I_p$ given to it, by the kinetic energy of the impinging electrons. These are usually made of nickel or molybdenum for general use.

Evacuation is usually carried to a pressure of 10^{-2} bars or less or about 10^{-5} mm. of mercury (1 bar= 1 dyne cm.^{2}). In manufacturing the electrodes, the electrodes and containing vessels are heated as a whole directly, and where practical, also by induction and by impact of electrons to a degree sufficient to remove all occluded gases.

The extent through which this process is to be carried depends upon the purpose for which the bulb is designed.

295. The Electrode Tube Operation :—If the filament F be heated by a set of batteries (a) in the Fig. 5·41 and then connected to the filament through another set of batteries (b) and the filament current is kept constant while the voltage E_p of the b-battery is varied, then the plate current, as indicated by a D. C. meter, will vary according to the curve I_{f1},

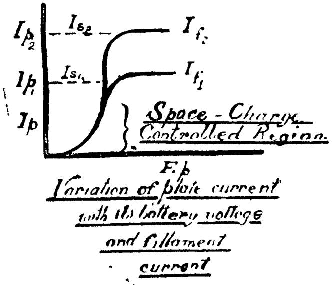


Fig. 5·40.

given in Fig. 5·40. Again, if the filament current is varied (say increased) to the value If_2, and E_p varied from zero to certain positive value, the curve If_2 will be, as shown in Fig. 5·40. I_{p1} is the maximum value, the plate current can have, regardless of E_p for a given heating filament current If_1. Similarly, I_{p2} is the maximum plate current that can exist for a given filament current If_2.

This value of plate current which can be further increased in *b*-battery voltage, is known as saturation current and is given by the equation (1). The region of the characteristic beyond which the plate current no longer increases with the increase of plate voltage to any value is known as the voltage saturation region. The value of this current is given by equation (1), p. 435. Such a two-electrode tube is a unilateral circuit element while ordinary metallic conductor, for example, *is bilateral.*

296. Two-Electrode (Diode) Valves :—The component parts of a diode valve are given in the Fig. 5·41 diagrammatically.

The vacuum bulb or vacuum tube, as it is sometimes called G, consists of a hot filament or cathode F, which acts as a source of thermionically emitted electrons and a cold plate P or anode. The filament is heated to incandescence by a set of batteries '*a*' to emit the electrons. This emission of negative charges causes a current to flow across the vacuum in the direction P to F and then completes its circuit through the set of batteries '*b*'.

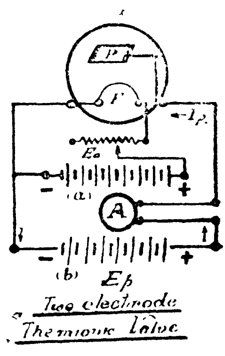


Fig 5·41

It is evident from the Figure 5·41 that the plate is positive with respect to the filament, and the flow should stop if the polarity of B is changed ; actually, under certain conditions, there is a slight flow from F to P, but for all practical purposes, the device may be taken to possess unilateral conductivity, and, therefore, may be

used for the purpose of rectification in any of connections given below.

297. Space-Charge Effect:—If the filament (of heating) current is increased keeping E_p constant, a point will be reached beyond which the plate current ceases to increase even though the filament heating current is increased. This is contradictory to the indication given by equation (1).

This limiting value of plate current is known as the temperature saturation value. The factor limiting the plate current within this region is the space volume density of the electrification filament and plate. If there were no space charge effect between the filament and the plate, the values of currents I_{p1} and I_{p2} would be instantly reached regardless of the value of E_p.

For control of space charge effect, interpose a grid or screen like electrode in the space between the filament and plate of a two-electrode tube.

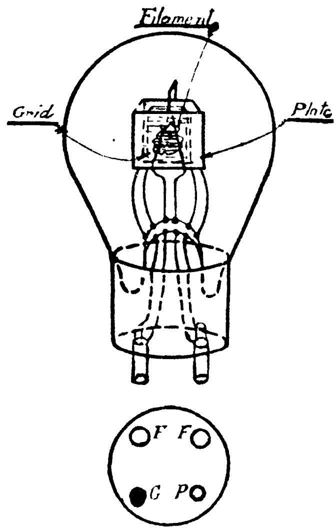
298. Evaluation of Space Charge:—Within the operating region controlled by the space change, the plate current is often given by:

$I_p'' = K E_p{}^n$, where K is a constant; n varies from $\frac{3}{2}$ to $\frac{5}{2}$ for various two-electrode and three-electrode vacuum tubes.

299. Space Charge of Rectifiers:—In a high-vacuum rectifier in which the cathode can supply more current than is being drawn from it, there must be a positive electric charge on the anode equal and opposite to the total charge of the electron in the space between the electrodes, the lines of electric force leaving this anode charge end on the electrons. If this were not so, there would be a potential gradient at the cathode, which would either force back the electrons emitted or else put into the space charge in greater number the electrons which are assumed to be available. Neither of these alternatives is consistent with a steady current, and a steady current means the existence of a definite electric field and corresponding potential drop across the tube. If the electrons had no means and moved with infinite velocity, this would not be true, but such is not the case.

They are emitted by the cathode at a very low velocity, and are accelerated in their passage to the anode by the electric force acting on them, in much the same manner, as the familiar objects pushed off and elevated platform would move with an acceleration due to the gravitational field. In both cases kinetic energy is acquired during the passage and dissipated at its termination. In the case of the electrons the energy heats the anode.

300. Three-Electrode Vacuum Tube or Triode Valve :—The tube containing a filament, grid and plate is known as a three-electrode rectifier or triode valve. The operating characteristic of three-electrode vacuum tube or triode valve may be expressed in two forms. First, as static characteristics, which are those obtained with D. C. measuring instruments relating to currents and voltages; second, as dynamic characteristics, or those obtained under conditions A. C. involving quantities. The static characteristics may yield useful information as to dynamic tube behaviour. In fact, certain dynamic characteristics may be obtained from the static characteristics. The static characteristics of the three-electrode tube, within the region where it is used as an amplifier, correspond, in some cases, to characteristics obtained from a generator by short-circuiting its armature terminals, Fig. 5·42.



Perspective and bottom view of base of a three electrode valve

Fig. 5·42

301. Tunger Rectifier or Hot-Cathode Rectifier :—When a metal is heated, until it glows, some of the electrons inside it are accelerated thermally to such volocity that they

leave the metal, overcoming the surface forces tending to retain them. The combination of such a heated metal with one or more other electrodes in a vessel has been made the basis of several types of rectifiers of the class known as valves described before. Of these, the types most used are the high-vacuum, hot-cathode types; hot-cathode gas-filled type; and the mercury-arc type. The Tungar rectifier consists of a Tungsten filament and copper or carbon anode mounted in a bulb filled with argon at a pressure, when cold, of from 3 to 8 cms. of mercury. Fig. 5·42 A

302. High-Vacuum Hot-Cathode Rectifiers:—If a cold and a hot electrode are sealed in an evacuated vessel and a positive potential is applied to the cold electrode, it will collect the electrons emitted by the heated electrode and by this means a current is caused to flow in one direction which can be reversed by a reversal of applied potential

303. Rating of High-Vacuum Rectifiers:—If the vacuum in a high-vacuum hot-cathode rectifier is brought to a high degree of perfection, it will be able to withstand a very high inverse voltage By building cathodes of large area, the current which can be carried will be increased, but there will still be space charge to contend with, and this often is the cause of a serious power loss. These two characteristics determine the field of usefulness of the device. If very high voltages of a rectifier with certain very definite clean-cut characteristics are required, the high-vacuum rectifier will be found well adapted to the task. If heavy currents are to be carried and efficiency is of importance, other rectifiers will be found to be more suitable. The sizes run from a few watts to 50 or 100 K V. A.

304. Hot-Cathode Gas-Filled Rectifiers:—In the hot-cathode gas-filled rectifier the cathode emits electrons, just as in high-vacuum rectifier because the temperature is so high that they can leave the metal against the forces tending o retain them One very successful design has a Tungsten cathode and is filled with argon. Positively charged argon ions neutralise most of the space charge, permitting the passage of current with only a small

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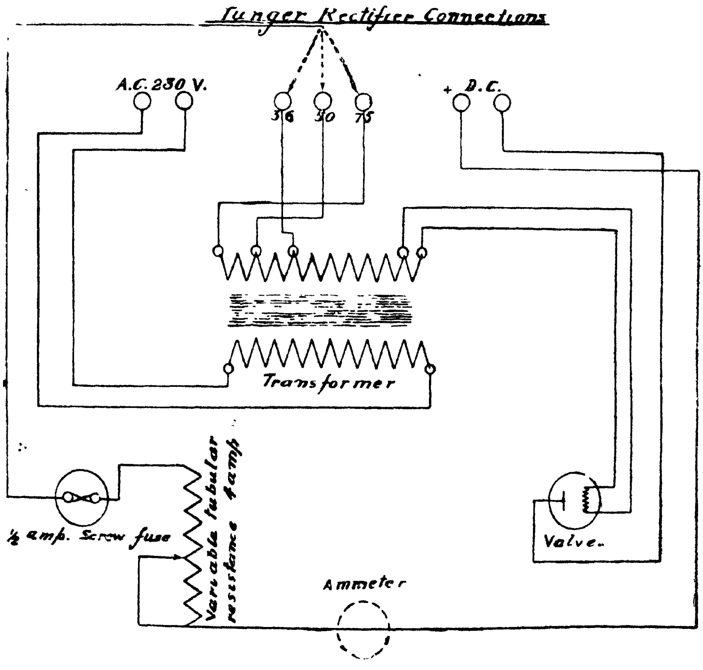

Fig. 5·42 A

loss. The anode may be of a variety of materials, but graphite is commonly employed. Since electrons are emitted only by the filament, or cathode, conduction of current occurs in only one direction.

Hot-cathode gas-filled rectifiers run at a gas-pressure of from 0·01 mm. to several centimeters. With the higher pressure they break down at a fairly low potential and carry current in reverse direction. There is also a slight voltage required to cause the current to start to flow in the normal direction.

305. Use:—This rectifier has been especially designed for the trickle charging of the small batteries used for the tripping circuits of oil switches in central and sub-stations. It is provided with three tappings and the secondary side of the transformer and an 8·75 ohms series resistance for adjustment of charging current in between these tappings. This resistance once set for a battery is recommended to be locked in one position. These arrangements give the rectifier great flexibility and enable it to deal with a large number of different voltage batteries, though it is only intended, of course, for charging a single battery at a time The more common batteries for tripping duties have 12, 15, 18, 25 or 37 cells of the lead type or 16, 20, 24, 33, 34 or 50 cells of the nickel iron type. All these can be trickle charged on this rectifier, if of suitable size, at rates round about one ampere or, of course, less. It should be noted that this rectifier in common with all other types of rectifying apparatus, delivers unidirectional but not continuous current. Thus the R. M. S. and average value of the output current are not equal and it is, therefore, essential, if true charge readings are to be obtained, any meters that may be employed on the D. C. side, should be of the moving coil or the *D.'* Arsonval type.

On no account should the D. C. voltage, backed down to this rectifier, be allowed to exceed 80 volts as read by a moving coil voltmeter with the battery connected.

It should further be noted that, being a half wave rectifier, should voltage reading be taken on the D. C.

side with the battery disconnected, only about half the time, volt will be recorded by the meter. This method, therefore, is unreliable and voltage reading should always be taken with the battery connected.

The rectifier consists of the instrument itself in a self-contained case and the valve for performing rectification.

306. Installation :—The rectifier, when sent out, has no control gear, other than the sliding resistance and three secondary tappings for control of the charging rates. It is, therefore, usual to instal it to the rear of one of the main panels and provide a D. P. switch fuse in the main A. C. circuit.

No switchgear is necessary on the D. C. circuit side of the rectifier and this is in any case adequately protected by a built-in fuse contained in the rectifier case. The actual connections are very simple. *There is a terminal block with rectifier.* The A. C. supply is brought to the two terminals marked A. C. at the left hand of the block. The wander lead (red-covered) is then set in the appropriate terminal 36, 50 or 75 marked with the voltage reading according to that of the battery in use. Finally, the battery itself is connected to the two right-hand terminals of the block, taking care to observe the correct polarity.

The rectifier is operated simply by making or breaking the A. C circuit as the case may be.

Should the battery with which it is desired to use the rectifier have a greater number of lead-acid cells than 18 (or their equivalent in nickel-iron cells), it is desirable to obtain the best life from the valve, that not more than this number be connected to the rectifier for the first two hours of operation, and, if possible, after this the number should be raised gradually to the maximum. By this process the valve is "re-aged." It is originally "aged" at the factory, but gets shaken up in the transit making it desirable some such treatment as above. Indication that "aging" is necessary, is provided by a green glow in the valve. This will only occur when the valve is new. The normal light emitted by the valve is purplish in colour. If any quantity of green light is present,

proceed as above. It is worth while remembering that the life of the valve bears a close inverse relationship to the D. C. current passed through it. Therefore, by keeping this current to the lowest value, maximum life is insured.

A spare valve should always be kept in hand and, if possible, be aged as described under "operation" above. Preferably it should also have performed a complete change in addition (say, 12 hours working) before being placed in reserve.

307. Defects and Remedies :—These are practically restricted to the fuse and the valve. If on switching on the rectifier, the valve does not light up then either—

(*i*) The A. C. supply is not connected up.

(*ii*) The valve is not screwed far enough into its holder or,

(*iii*) If the valve filament has failed, try a new one.

If on switching on the rectifier, the valve lights up, but no D. C supply is obtained, then either—

(*a*) The 2½ amperes fuse has blown off, in which case replace. (Accidentally reversed battery connection will always blow this fuse).

(*b*) The anode contact made by the spring clip on the valve holder to the skirt of the valve cap, is deflected. Bend the clip till good contact is obtained with the valve skirt

(*c*) If the valve is defective, try a new one.

308. Hot-Cathode Rectifier (mercury). Fig. 5'36.

Elements—(1) A hot cathode

(2) A cold anode

(3) A highly evacuated tube in which a small amount, a single drop, of mercury is placed in the coldest part of the tube.

The temperature of the mercury which does not form the cathode, determines the pressure of the conducting mercury vapour. The current passes through the tube as an arc, always in one direction, when the voltage exceeds the critical voltage. The hot cathode replaces

the mercury pool of the mercury arc rectifier and each anode in the mercury arc rectifier is replaced by the plate of the hot-cathode rectifier.

Use :—Rectifying alternating currents, to meet large direct-current power requirements.

Two element tubes, with mercury vapour, amplifier conduction.

309. Hot-Cathode Mercury Rectifiers *versus* Mercury Arc-Rectifiers.

In the former we have—

(1) Smaller sizes for the same rated capacity.

(2) Shorter distance between cathode and anode, and hence lower voltage drop in the arc.

(3) Lower cathode voltage drop, to barium-coated cathode.

(4) Higher efficiency of rectification as the total voltage drop in the hot-cathode rectifier is about 12 volts as compared to about 21 volts in the mercury-arc rectifier.

(5) Freedom from back firing.

310. Thyratrons :—*Vide* Fig. 5·37.

Elements—(1) A hot cathode, (2) A grid.

(2) A cold anode and usually a drop of mercury which provides the conducting vapour. Argon, Neon, or Helium gas may be used in place of the mercury vapour.

Action.—The starting of the current, which passes through the tube as an arc, is controlled by the grid voltages. After the current starts, the grid voltage has no influence until the anode voltage becomes zero after which the starting process repeats. With alternating currents the anode voltage is zero twice for each cycle. The current flows in one direction only. Hence, each thyratron produces a pulsating unidirectional current. If alternating currents are impressed on the grid, the magnitude and time phase of the grid voltage, with respect to the whole alternating current, determine the fraction of each positive half wave that current will flow in the tube, *i.e.*, the average value of the current output can be controlled by varying either the time

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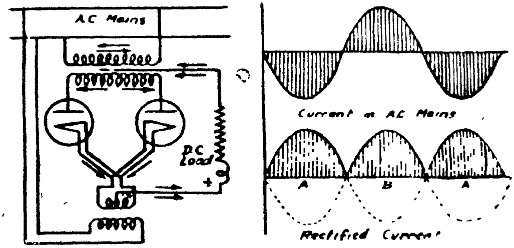
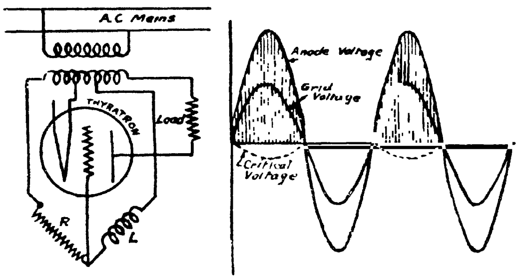
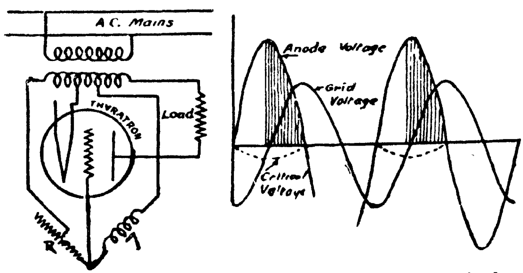


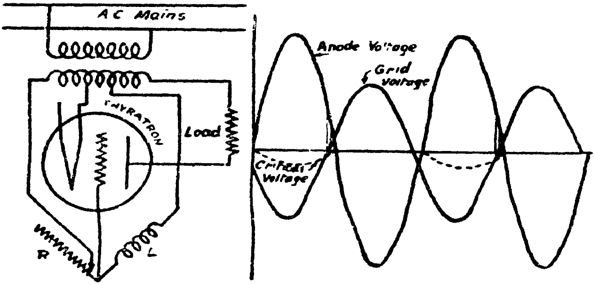
Single-phase Circuit Diagram for Rectification by Hot-cathode Rectifier
Fig. 5·36



Control Characteristics of a Thyratron on which alternating currents impressed on both the Anode and the Grid are in time-phase.
Fig. 5·37

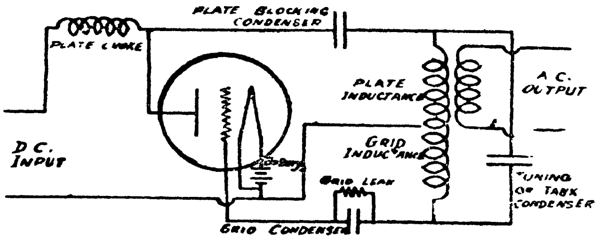


Control Characteristics of a Thyratron in which the time-phase of grid voltage lags 80° behind the load current voltage.
Fig. 5·38



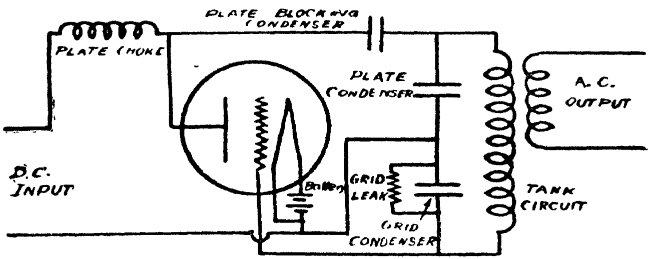
Control Characteristics of a Thyratron in which the grid voltage is nearly in opposition to the anode voltage.

Fig. 5·39



Circuit Diagram for Hartley Vacuum Tube Oscillator.

Fig. 5 39A



The Colpitts Circuit for Vacuum Tube Oscillator.

Fig. 5·40

phase or the magnitude of the grid voltage. By changing the resistance of the grid circuit from infinity to zero the grid voltage is retarded 180°. Current starts as soon as the grid voltage is less negative than the critical voltage and the flow continues practically for the full positive half cycle, and repeats in successive cycles. By changing the time phase of the grid circuit so that it lags 80° behind the anode voltage, the start of the current flow will be delayed and the average current reduced in proportion to the shaded areas as in Figs. 5'38 and 5'39.

By the phasec-ontrol of the grid voltage with respect to the load or anode voltage the average value of the current can be varied from a maximum to zero by changing the resistance in the grid circuit from infinity to zero.

The phase-control of the grid voltage may be obtained by a combination of condensance and inductance in the grid circuit, in place of the inductance and resistance. The vacuum required for operation is from 1 to 100 microns. The internal voltage drop of the mercury vapour thyratron is about 12 volts; the same as for the two-element hot-cathode rectifier. The cathode excitation requires less than a watt per ampere so that the over-all efficiency of the thyratron is higher than for mercury-arc rectifiers or rotary converters.

311. Oscillator or Inverter--Fig. 5'40.—In this, the tubes used are called thyratrons, as distinguished from the ordinary vacuum tube by the presence of mercury vapour inside the bulb. The effect of this mercury vapour is such that no plate current will flow while the grid is negative with respect to the filament, but that once the plate current has started, the grid no longer controls it. The plate current can be stopped only by removing the plate potential.

Operation.—In Fig. 5'41 suppose that the thyratron A draws current. The current will flow through it and charge the condenser C_2. It will also flow through R_2 keeping the grid on thyratron B negative so that it cannot draw current. When condenser C_2 becomes fully charged,

the plate current in thyratron A ceases, thereby opening the low-impedance shunt R_1 C_1. The negative voltage on the grid of thyratron B is removed and the tube will then draw plate current causing C_2 to discharge and C_1 to charge. The discharge current of C_2 flows through R_1 keeping the grid of tube A negative so that no plate current can flow through this tube. When C_2 is fully discharged and C_1 fully charged, the plate current to tube B ceases, the negative voltage on grid of tube A is removed and tube A again draws current. The cycle is repeated at a frequency determined by the frequency of the grid transformer.

Advantage:—Due to the low internal drop in the tube the efficiency of thyratron OSCILLATORS OR INVERTERS, as they are usually called, is quite high, being higher than that of inverted rotary converters. They have the advantage of quiet operation, no wear and quick starting with reasonably low first cost, low maintenance and long life.

Use:—Vacuum tube oscillators find their greatest application in radio communication, as practically the only means for efficiently producing high frequency alternating currents

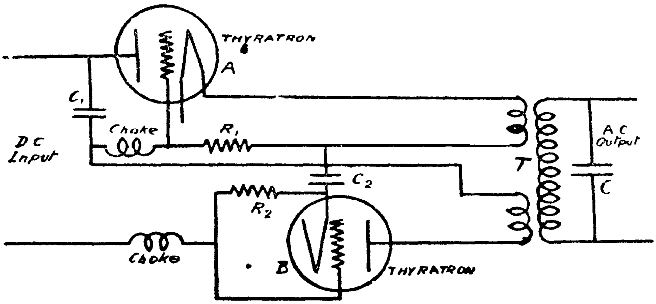
Oscillators have been used to produce frequencies of any desired value up to 30,00,00,000 cycles per second.

The thyratron inverter is more satisfactory than the regular vacuum tube oscillator where large currents are involved due to its low internal drop. The standard vacuum tube has an internal impedance of several thousand ohms and requires up to several thousand volts for operation. The thyratron operates with an internal drop of approximately 12 volts for all values of the load current.

At present thyratron inverters find their chief application in the conversion of direct currents to alternating-current power in small units

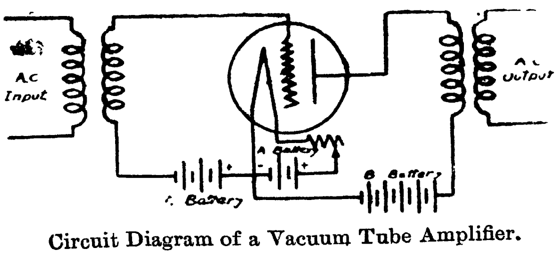
Amplifiers

312. Operation:—Alternating current is applied to the grid of the tube through the input transformer. As



Self controlled Series-type Inverter. The frequency is determined by the characteristics of the Grid Transformer.

Fig. 5 41



Circuit Diagram of a Vacuum Tube Amplifier.

Fig. 5'42

the grid voltage increases, first in a positive direction, and, then, in a negative direction, the valve action of the tube causes the plate current to rise and fall. This pulsating plate current in turn flows through the output transformer and induces an alternating current voltage in the input circuit. If the potentials of the *B* and *C* batteries (Fig. 5·42) have the proper values, the alternating-current output will have exactly the same wave shape as the alternating current input, but its magnitude will be greater as a result of amplification of the vacuum tube.

Note the Supply and Distribution of Energy, etc.

(1) The entire energy in the alternating-current input circuit is consumed in supplying losses in the grid circuit; none of it appears in the plate circuit.

(2) All of the power output of the plate circuit and the losses in this circuit are supplied by the *B* battery under control of the grid.

(3) The potential of the *C* battery is made at least equal to the maximum value of the alternating-current input voltage to the grid in order to keep the potential of the grid always negative with respect to the filaments.

Use:—Vacuum tube amplifiers are ideal for amplifying the complex wave shapes found in communication work, and are used largely in the radio and telephone communication field. They are also used to a limited extent in controlling relays and protective devices, and in moving-picture field to produce and project sound moving pictures.

Adopted from " Alternating Currents " by C. E. Magnusson.

CHAPTER VI

SECONDARY BATTERY ENGINEERING

313. General Lay-Out and Design of Battery Room.

(*a*) **Size of Room:**—It depends on (1) the size of the battery, (2) number of cells, (3) manner of installing. Take about 3′ between each row. If they are arranged back to back, keep a foot between them. The size of the battery-room should be sufficient to allow easy access for the inspection, testing and repairing of every individual cell, also for general overhauling of the battery.

If the size of the room available is not fixed, or if a new building is to be errected, allow, as a rough guide, a proportion of length to width of approximately between two and four to one. Assume a maximum width of single span of roof of about thirty feet. For greater widths, treat each span as a separate room. The ceiling should not be above 20 feet.

(*b*) **Location** :—The room should be sealed from the rest of the building, and located near the generating machinery and distribution switchboard, so that the copper cables may be low in cost. An entrance from the battery room should be provided from the open air and not from the engine room only. The room for this purpose should be dry, well-ventilated to maintain the insulation at a high point, and of a moderate temperature to work the battery satisfactorily to avoid explosion, etc. The floor, walls, and ceiling must be of some acidproof material, brick or tile being preferable with a layer of asphalte. The floor must be so made as to drain readily, an outlet being provided to the drainage system and there should be a gradual slope from the central line of the room towards the walls to carry away easily all water and washing through a small drain which should run all round the walls emptying itself in an out-let outside the room.

Any woodwork or ironwork in the room should be coated with asphaltum or any other suitable paint.

(*c*) **Ventilation** :—Suitable outlets in the ceiling or roof with inlets of double the area near the floor will usually be sufficient, though in some cases forced draught may be necessary. The best results can be obtained from the battery at a temperature between 50° to 80°*F*., and 80°*F*. is the maximum temperature in which the battery will work satisfactorily, as high temperature increases the capacity but decreases the life of the cells. But low temperature reduces the available capacity temporarily but does no injury.

(*d*) **Light** :—There should be sufficient illumination so that all parts of the battery can be readily inspected at any time, day or night. A north light is very desirable. The cells must be protected from direct sun-rays, as the heat might crack the cells (glass) or increase the activity of the acid, which is not desirable. All windows permitting sun's rays should be of frosted glass or else coated with some white paint. A portable lamp attached to a plug in the lighting circuit should be used for inspecting the cells at night.

(*e*) **Cleanliness** :—The battery room and all apparatus therein should be kept thoroughly clean. If the floor, metal work, stands, insulators, trays or tanks become coated with acid-laden moisture, wash them with a solution of washing soda and water; then rinse with fresh water and cover them liberally with vaseline and open all the windows to allow of complete drying. Do not, at any time, allow the corrosive products or the washing solution to fall into the cells. The battery room should also be provided, if possible, with sufficient provision for getting water from suitable water-taps, etc. Aluminium may be used with advantage in the battery room and does not require paintings in any way.

314. Battery Room Auxiliaries :—Milking booster, two lead-lined tanks, voltmeter, cadmium pencils, hydrometers, cell lamps, thermometers log-book, jumpers with suitable terminals, small rubber piping and jugs for carrying acids.

315. Types of Plates or Cells :—I. Acid Cells : (1) **Plante plates,** formed electro-chemically ; (2) **Pasted plates,** in which material is added as paste ; (3) **Iron clad**—where the positive plates are made up of hard rubber-clothed tubes containing the active material.

II. Alkaline Cells :—Caustic potash for electrolyte and nickel peroxide and iron for the electrodes.

316. Setting Up the Cells.—The battery is usually placed on the floor, or upon strong wooden shelves. With lead-lined, wooden tanks, the cells are set directly on glass insulators of special form, there being four insulators under ordinary size cells and six where cells are so long as to require middle support. Large cells are set with double insulation, that is, the cells are set on insulators—these insulators rest on a wooden framework, and the wooden framework rests, in turn, on a set of insulators. For small glass cells, make a shallow wooden box, an inch deep, having a length and breadth greater than the corresponding cell dimensions. Set this box on four glass insulators and fill it with clean sand. On this sand, the cell is set. The cells should be insulated from each other. Wooden stands should be varnished, painted, or soaked in paraffin. It is important to have every cell accessible for inspection, cleaning, and removal, it being desirable to reach both sides of the cell. There should also be sufficient head-room between shelves so that the elements may be lifted out.

Test the polarity of each cell and of the circuit before making connections. Note that the nomenclature of storage batteries is different from that of primary cells. *The positive plate* in the former is the peroxide plate (brown), and is that one from which the current flows out in discharging; whereas that would be *the negative plate* of a primary battery. The colour of the plate is the best indication of its polarity, the positive plate being a light brown when discharged and a chocolate colour when charged, while the negative varies from a light to a dark slate colour. The polarity may be tested with

any form of pole-tester, or by the positive expedient of dipping the terminals in dilute sulphuric acid, the one from which the most bubbles arise being the negative, and the positive lead wire will be turned brown—care must be taken to keep the ends at least an inch apart in order to avoid the danger of short circuit.

317. Cell-Covers.—The cell-covers made of glass plates or spray arresters are used to reduce the diffusion of acid, the amount of electrolyte. The covers should be removed occasionally and washed in clean water.

The use of oil or paraffin on the surface of the electrolyte to prevent spraying is not a good practice.

318. The Most Convenient Way of Planning an Installation.—Is to decide upon the following points:—

(1) *Type of cell*, say (chloride, plantide or exide).
(2) *Size of cell* (size of plate and number of plates).
(3) *Material of containers* (glass, lead-lined wood or sheet lead)
(4) *Number of cells* in a battery.
(5) *Number of regulating* cells.
(6) *Stands or stillage* for support of cells.
(7) *General lay-out* of battery room.

Example 1. A stationary battery is required to give 60 amperes for ten hours on a 220-volt circuit. It will also be required to give 150 amperes for short periods of, say, half an hour.

(1) *Type of Cell*:—Assume that the "CHLORIDE" type of cell has been decided upon.

(2) *Size of Cell*:—It is a good policy to select a cell somewhat larger, rather than smaller, than is indicated by the estimated requirements. See Catalogue of "THE CHLORIDE ELECTRICAL STORAGE CO., LIMITED," for example of chloride cells. From ten-hour column under "Discharge current in amperes" SLIG 10 will give 61 amperes for ten hours to a final voltage of 1·83 volts per cell. It will also give 150 amperes for some period between one and three hours. It is plain, therefore, that the ten-hour discharge is the determining factor.

(3) *Material of Containers* :—Generally speaking, glass is the most suitable material when available; next in order of reference comes lead-lined wood, and lastly sheet lead. Here, say, glass is selected.

(4) *Number of Cells in a Battery* :—From the list of capacities of cells find the final voltage per cell when the heaviest discharge current is carried for a complete discharge. Then,

$$\text{Number of cells in a battery} = \frac{\text{Minimum line voltage permissible at the end of heaviest discharge}}{\text{Final voltage per cell when on heaviest discharge}}$$

$$=220/1{\cdot}83=120.$$

For calculating the number of cells required for a battery of a given voltage, the following minimum values of the voltage should be taken as a basis :—

For discharge	at	the	10-hour	rate	1·83	volts	per	cell.
,,	,,	,,	5	,,	1·83	,,	,,	,,
,,	,,	,,	3	,,	1·83	,,	,,	,,
,,	,,	,,	2	,,	1·75	,,	,,	,,
,,	,,	,,	1	,,	1·75	,,	,,	,,

The maximum voltage at the end of the charge depends on the rate of charge. At the rates given in the list, it is about 2·75 volts per cell.

The number of cells required will be equal to the quotient obtained by dividing the busbar voltage, by the minimum volts per cell, at the maximum current at which the battery will work continuously. The higher values, *viz.*, 1·83 volts, should not be assumed unless the discharge current will not be greater than the 5-hour rate.

The regulating cells should be connected to the regulating *switch in steps, the number of cells per step* and the number of steps depending on the value of the busbar voltage. The number of cells per step may vary from 1 to 3, the smaller steps being next to the main body of the battery, and the larger at the end, so that the larger steps are called into use at the end of the discharge when the voltage is falling most rapidly.

(5) *Number of Regulating Cells* :—

(For "Chloride" Cells) = Number of cells in battery —Line volts./2·65

= 120 − 220/2·65 = 120 − 83 = 37. Allow for fine regulation between cells 220/2·05 and 220/1·9 = 107 and 116. The connections to the regulating switch may, therefore, be from cells 83, 87, 91, 95, 99, 102, 105, 108, 110, 112, 114, 116 and 120, requiring a thirteen-point switch. The variations in voltage, when the regulating switch is operated, will be approximately 4 volts per point when the cells in circuit are between 108 and 116.

In many modern stationary batteries, regulating switches are more or less eliminated by the use of automatic boosters in which the field is produced by the resultant effect of similar distinct windings. One winding will cause the E. M. F. of the booster to vary with the load while another will take into account the state of the battery. In this way the pressure of the supply is maintained practically constant and the battery caused to charge or discharge according as the load on the station is above or below the normal.

(6) *General Lay-out of Battery* :—Say, Single Tier Stands. First determine upon number of rows. As a rough guide, the following empirical formula may be used :—

Number of Single Rows :
(Single tier) = Number of cells in battery/50 + $1\frac{1}{2}$.

Now group these rows, into single tier, noting that an even number of rows generally gives shorter connections to the switchboard.

General Lay-out of Battery Room :—
Number of single rows = Approximately 120/50 + $1\frac{1}{2}$ = $2\frac{1}{2} + 1\frac{1}{2} = 4$.

Place these out as 4 single rows.

319. Connections :—The connections between the various sections of the battery and between the battery and the switchboard may be of copper rod or bar, coated

with vaseline, acid-proof enamel, or a mixture of tallow and white-lead to protect them from corrosion. As the lengths are generally short, the size is determined by the current-carrying capacity. For lighting batteries, the current may be based on the three-hour rate of discharge in amperes. For traction batteries, the basis should be the one-hour rate of discharge in amperes—*the grey ones* of one cell being connected to the positive plates, *the brown ones*, of the next. Before connecting up, however, the contact surfaces must be thoroughly scraped and cleaned, then coated with acid-proof paint to avoid corrosion. The *greatest care must be exercised in obtaining a good electrical contact.* Keep all connections clean and tight. Inspect at regular intervals. The best time for doing this is towards the end of a charge, testing with the bare hand to detect an increase in temperature, which will denote dirty or loose connection. During the first charge feel the sheds or the junction points. If they are hot, tighten the joints by the nuts or better solder.

320. Dynamo :—The dynamo should be of the shunt-wound type. If compound-wound, the "series" portion of the field coils should be cut out when the dynamo is being used for charging the battery. Under these conditions, it must be capable of giving continuously the normal charging current in amperes at a voltage of (No. of cells in battery $\times$ 2·4) volts. It must be capable of giving for two hours, half the above current in amperes at a voltage of, say, (No. of cells in battery $\times$ 2·65) volts for "chloride" cells.

321. Switchboard :—All switchboards should have mounted upon them.—

A. An ammeter or ammeters in the battery circuit showing the value of charge and discharge current which is proposed to put on the battery during charge or discharge, respectively.

B. A voltmeter, arranged to read (1) the generator volts, (2) the battery volts on the charge side of the regulating switch, (3) the battery volts on the discharge side of the regulating switch.

C. Switches suitable for regulating the number of cells in circuit. These vary with the system of regulation adopted.

D. An auto-cut-out switch is generally desirable to ensure that the battery is cut in and out of circuit at the correct moment when starting or stopping a charge.

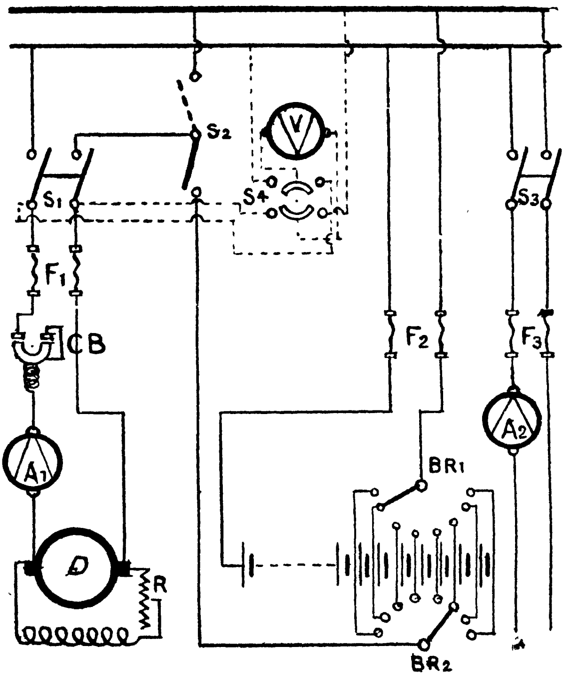


Fig. 6'01
Switchboard for Small Lighting Plant with Double Battery Regulating Switch.

E. Main switches and fuses are required

Note that the machines are compelled to run normally at an output far below their maximum and thus the capital outlay is unnecessarily large. This disadvantage is completely removed by the use of booster when the

principal machine can be designed for the normal supply pressure without any provision for a large increase of pressure. The iron of the machine can be highly saturated thus reducing the size and cost of the machine. A farther saving is effected in the field rheostat which need not be so large.

The main dynamo is connected permanently to the discharge switcharm, while the booster is connected between the two switcharms and charges the cells lying between them. If the excitation of the booster is

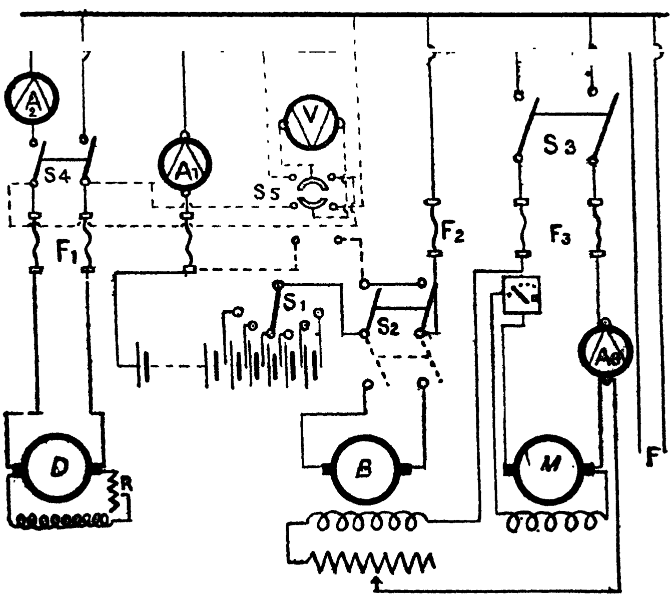


Fig. 6'02.

Switchboard for small Lighting Plant with Battery and Booster

adjusted until its current is equal to the charging current through the main battery, no current will flow throug the discharge switcharm. The latter will then resemb

the galvanometer connection in the Wheatstone bridge in that it connects two points at the same potential. The battery will then act simply as a pressure regulator.

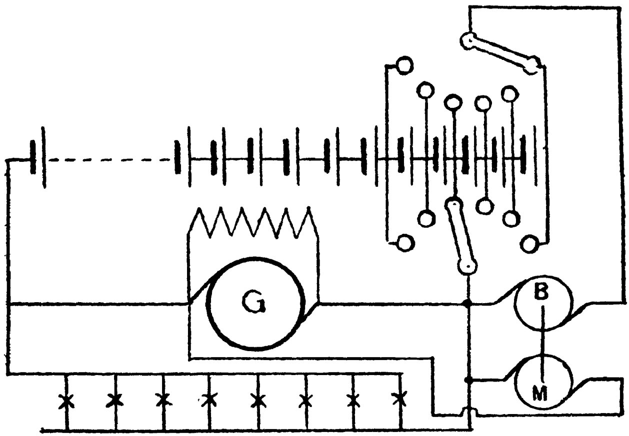


Fig. 6·03.

322. Battery Booster:—With reversing switch in the field circuit and a hand-regulated field rheostat

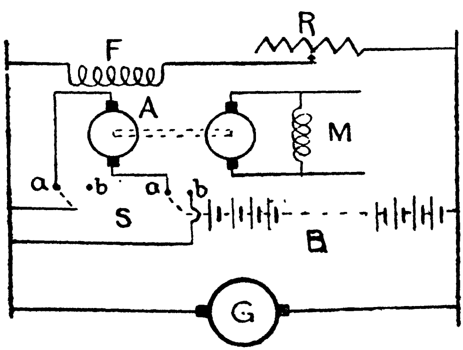


Fig. 6·04.

very often it is necessary to charge a battery having a higher voltage than that of the charging generator by having a dynamo generally of the shunt type in series with the busbar. By varying the field, the busbar voltage plus the booster voltage may be made greater than the voltage of the battery.

323. Three-Wire System with Battery and Booster :--In the three-wire system, the neutral wire is joined at the central station to the middle of the balancer and the middle of the battery. Each half of the battery has a booster connected in its circuit and each half is managed quite independently of the other. The two boosters are often rigidly joined to a continuation of the shaft of the balancers. When any one of the balancers runs as a motor, it also runs the two boosters while driving the second balancer machine as a dynamo.

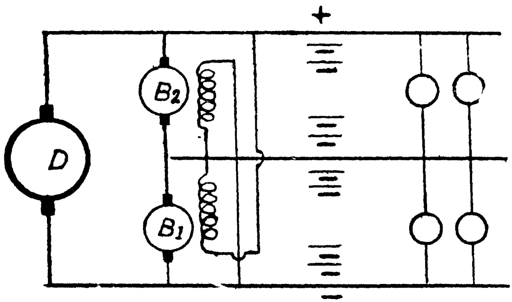


Fig 6'05.
Three-wire Distribution with Balancers and Battery.

324. Exciter Controlled Battery Booster :— In this, Fig. 6'06, there is a motor, but having a few series turns to compensate for its own armature reaction and drop, driving a generator and a shunt-wound exciter which supplies the current to the generator.

The voltage of the exciter, which is nearly constant, is balanced against the P. D. of the battery. When discharged, the terminal voltage of the battery falls and the current in the generator field is upwards and this excites the generator so as to aid the discharge. At the time of charging as the terminal P. D. rises and reverses the generator field current, the generator helps the charging of the battery.

(*a*) If the booster field is increased, a voltage may be obtained which is high enough to charge the battery, and a slight decrease in the booster field enables the battery to be safely discharged and the main dynamo is thus helped.

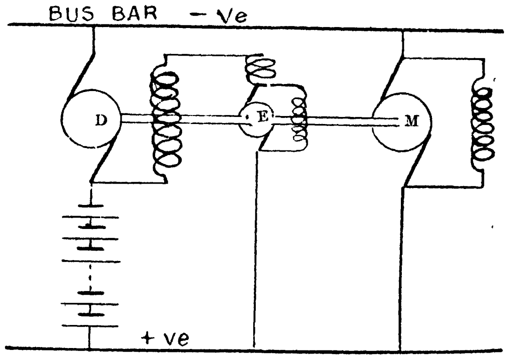


Fig. 6·06.
Highfield Battery Booster.

(*b*) On the other hand, if the battery voltage is much lower than the busbar voltage, the booster inserted in the battery circuit may have its field so regulated in direction and value that the booster voltage may oppose the busbar voltage and thus add to the discharge voltage of the cell. In this case, by slightly decreasing the booster voltages the battery may be safely charged and by increasing the booster volts the battery may be further discharged on to the busbars.

325. Booster is used (1) to reduce the pressure drop in the return feeders of a tramway and thus prevent large return currents straying from the rails.

(2) It is used in conjunction with a battery to keep the load on the generators almost constant although the load may vary.

(3) To charge up separately, any individual cell or group of cells by a small dynamo of low voltage

when it is called a *milking booster.* This small dynamo of low voltage is no booster at all in the proper sense of the term.

(4) Boosting in A. C. circuits may be done by using static transformers instead of rotary machines. The primary of the transformer is connected across, and the secondary in series with the circuit to be boosted ; and the variable ratio tappings regulate the voltage.

326. Capacity of the Booster :—The booster must be capable of carrying the full-load current ; and the K. V. A of the booster must be such as to supply the required boosting, *e.g.*, if 10 °/o boost be required, the booster K. V. A. must be 10 °/o that of the load supplied.

327. Filling Cells With Acid :—When everything is ready for starting up, the filling of the battery with acid may be commenced. For this purpose dilute sulphuric acid of 1·180 specific gravity must be used.

Purity of Acid.—As the satisfactory working and durability of cells greatly depends upon the purity of the acid employed in the cells, it is of the utmost importance that the concentrated acid and water, used for the preparation of the dilute acid, should be absolutely free from all impurities, such as chloride, nitric acid, ammonia, iron and other metallic impurities.

In order to reduce the freight to a minimum, chemically pure acid is purchased *in a concentrated state* (1·840 specific gravity) and supplied in stone or glass screw-stoppered jars (usually containing from 1 to 2 gallons of acid each), carefully packed in whiting. Such concentrated acid must be broken down with water in proportions by measure of 1 to 5·6, *i.e., 1 gallon of concentrated acid should be mixed with 5·6 gallons of water, which, however, will* only produce 6·2 gallons of dilute acid of 1·180 specific gravity.

Directions for Mixing Acid.—Fill up the tank, the capacity of which having been previously ascertained, to about three quarters with distilled water, and then pour in *very slowly* the prescribed quantity of concentrated acid, while constantly stirring the liquid by means of a

suitable wooden paddle. The stirring may also be effected by blowing air into the liquid through glass or rubber tubes.

It is not necessary to mix the whole of the acid at once, as the cells can be left standing for some time after filling with acid, before being charged ; this time of standing should not, however, exceed two weeks, otherwise the plates will become sulphated. The cells can, therefore, be filled up in batches.

On no account must the water be poured into the acid, as the mixture will then boil up and may seriously injure the operator. It must also not be attempted to mix the acid in the fitted up cells themselves, as irreparable damage would thereby be done to the plates

As the liquid becomes very hot in mixing, it must be allowed to cool down (it is best to let it stand overnight) to a temperature not exceeding 85 deg. Fahr. (35 deg. Cent.). It should be tested as to its proper strength with one of the hydrometers supplied with the battery. If the concentrated acid and water have been used in the right proportion, the hydrometer should read exactly 1·180 ; the liquid is then ready to be filled into the cells.

Care is necessary on the part of the operator, during the mixing and the filling in, to prevent the acid from splashing up into his face, and it is advisable for him to wear glasses to protect his eyes.

Level of Electrolyte :—The level of the electrolyte must never be allowed to fall to less than half an inch above the top of the plates. Any loss due to evaporation must be made up by adding pure distilled water, as above explained. Evaporation will be greatly retarded by the use of glass spray arresters covering the top of the plates or by an anti-spray oil film. Spray arresters must be so placed as to be easily removable for the purpose of examining the cells. Acid should not be added, except under the maker's advice.

328. Rules to be Observed in Connecting Batteries to Dynamos :—(1) If there is automatic cut-in switches, the attendant is to close the main switches with the shunt regulator in its lowest position when the

dynamo is generating a low voltage. The voltage is then gradually raised by the shunt regulator until the automatic switch acts and closes the circuit. Then move the rheostat to the proper position when the charging current is indicated by the ammeter in the battery panel of the switchboard.

(2) If there is no automatic switch (*i*) charge the central station or stationary battery at constant current throughout the entire period up to the cells gassing when the charging current should be reduced. Note that charging battery, by the constant potential method (using about 2·3 volts per cell), is generally used in batteries for propelling vehicles when the time spent on charging is of vital importance ; this gives a large rush of current into the battery and a heavy charge is given for a short time. The wear and tear is great, but the plates are made to stand such booster charges as economically and efficiently. (*ii*) Never close the switch so long as the voltage of the dynamo is less than the voltage of the battery. Increase the voltage of the dynamo, if necessary, by means of the field rheostat to get the proper charging voltage and current.

(3) Do not connect circuits whose voltages are not equal and opposite.

(4) Do not open a circuit carrying a large current and open it when the current is zero.

(5) Disconnect a dynamo or battery, manipulate so that no current is flowing in the circuit ; for this, switch-in the end cells, and reduce the voltage of the generator.

In central station, supplying traction, the battery is usually connected in parallel with the busbars. Under normal conditions the voltage of the battery and generators is equal. If the load increases, the battery discharges and supplies power for the peak load; if the load decreases, the generators charge the battery and the generators are thus always fully loaded.

329. Floating Battery :—As generally over-compounded generators are used in which the voltage increases with the load, a battery connected with the busbars only increases the fluctuation of the loads and does not help to keep the load constant.

Automatic reversible boosters, in which the booster armature is in series with the battery, are used to effect the above purpose. The booster plant and battery are called *floating battery.*

This is used as a battery connected across the line so as to charge, when the line potential is high; and discharge, when it is low. It is very little used excepting on a long line with light load and small feeders. This is usually located about 3/4ths of the distance from the power-house to the end of the line, or if the line is fed from both ends, midway between the feeding points.

Function of a Floating Battery :—(1) To improve the line voltage and displace a certain amount of feed wire. (2) To relieve the power-house of fluctuation of load. (3) To keep the cars moving when the power supply is temporarily interrupted. (4) To supply power for the operation of a few cars or light load at night when the power-house is shut down.

Example 2. A 600-volt power station feeds a trolley line 10 miles long, at the end of which is floated a storage battery of 520 volts E. M. F. and internal resistance 1 ohm. A single car taking a constant current of 60 amperes is running on the line. If the combined resistance of rail return and trolley wire is 45 ohms per mile, find the least voltage at the car and the distance at which this occurs.

Solution :—

Let X be the distance at which the least voltage occurs.

Let V be the voltage and I_1 the current supplied by the battery.

$$V = 600 - (60 - I_1)\, X \cdot 45$$
$$V = 520 - I_1 \{ (10 - X) \cdot 45 + 1 \}$$
$$\therefore 80 + 5{\cdot}5\, I_1 - {\cdot}45 \times 60 \times X = 0.$$
$$\therefore I_1 = 4{\cdot}9\, X - 14{\cdot}5.$$
$$V = 600 - (60 - 4{\cdot}9\, X + 14{\cdot}5)\, X \times {\cdot}45$$
$$= 600 - {\cdot}45\, X\, (74{\cdot}5 - 4{\cdot}9\, X)$$

$\dfrac{dV}{dX} = -{\cdot}45\,(74{\cdot}5 - 9{\cdot}8\, X)$, this is zero when $74{\cdot}5 = 9{\cdot}8\, X$

and $\dfrac{d^2 V}{d X^2} = + \cdot 45 \times 9 \cdot 8$ is positive.

$\therefore$ V is minimum when $9 \cdot 8 \, X = 74 \cdot 5$

$X = 7 \cdot 6$ miles.

$V = 600 - 45 \times 7 \cdot 6 \, (74 \cdot 5 - 4 \cdot 9 \times 7 \cdot 6) = 472$ volts minimum voltage.

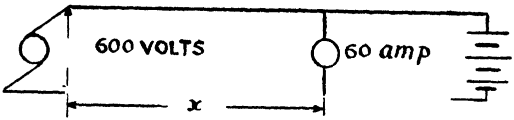


Fig. 6·07.

Example 3. A floating battery having an E. M. F. of 500 is situated at the end of a trolley line 10 miles long and resistance ·4 ohms per mile. If the resistance of rail return is ·05 ohm per mile and station voltage is 600, what will be voltage at car taking 83 amps., when at the centre of the line ? What will be the current supplied by the battery ? Internal resistance of battery 1·2 ohms.

Solution :—

Let V_1 the voltage at the car and I_1 be current supplied by the battery.

Then—

$500 - V_1 = I_1 \{ \overline{(\cdot 40 + 05)} \, 5 + 1 \cdot 2 \}$

$600 - V_1 = (80 - I_1) \, (\cdot 40 + 05) \, 5 \, ; \; 5 \cdot 7 \, I_1 = 82$

$I_1 = 14 \cdot 02$ battery current.

$V_1 = 600 - 65 \cdot 98 \times 2 \cdot 25 = 452$

Example 4. In the previous example find the voltage at the car when situated near the battery and the battery current. What would be the voltage if the battery were disconnected ? Find the maximum charging current.

Solution :—

$I_1 \times 1 \cdot 2 = 500 - V_1$

$(80 - I_1) \, (\cdot 40 + \cdot 05) = 600 - V_1$

Hence, $I_1 = 45{\cdot}6$ current supplied by battery.

$V_1 = 445{\cdot}28$ volts.

$V_2 = 600 - 80\ ({\cdot}40 + {\cdot}05)\ 10 = 240$, this would be voltage at the car if the battery were disconnected.

The maximum charging current of the battery is given by—

$$I_{\text{max.}} = \frac{600-500}{({\cdot}40+{\cdot}05)\ 10+1{\cdot}2} = 17{\cdot}6 \text{ amps.}$$

This occurs when no car is taking current.

Example 5. A floating storage battery is situated at the end of a transmission line ·5 ohm resistance, where a constant load of 250 amps. is delivered. The station voltage is 500 volts. If the E. M F. of each cell is 2 volts and internal resistance, ·002, determine the number of cells required and their capacity if the load is to be supplied at 440 volts.

Solution :—

Let I_1 be the battery current and N the number of cells—

$$(250 - I_1)\ {\cdot}5 = 500 - 440 = 60$$

$$\therefore I_1 = 130 \text{ amperes discharge rate.}$$

$$2\ N - 130 \times N \times {\cdot}002 = 440$$

$$(2 - {\cdot}26)\ N = 440$$

$$\therefore N = 252{\cdot}8, \text{ say, } 253 \text{ cells.}$$

Example 6. At the end of a transmission line, having a resistance of ·2 ohm, is situated a load of 500 amperes for 10 hours a day. The generating station operates continuously at 550 volts. A floating storage battery is to be installed at the end of the line to equalise the load on the station.

How many cells should be used so that the total ampere-hour charge should be 5 % greater than the discharge ? What will be charging and discharging currents and voltages ?

E. M. F. of each cell 2 volts assumed constant, internal resistance ·0004 ohm per cell.

Solution :—

Let I_2 be discharging current for 10 hours when load is on.

$\bar{I_2}$ be charging current for 14 hours when load is off.

V_1 and $\bar{V_1}$ the respective voltages and N the number of cells.

$$10\, I_2 \times \frac{105}{100} = 14\, \bar{I_2} \qquad \ldots \qquad (1)$$

$$\cdot 2\,(500 - I_2) = 550 - V_1 \qquad \ldots \qquad (2)$$

$$2\,N - \cdot 0004\,N\,I_2 = \bar{V_1} \qquad \ldots \qquad (3)$$

$$\bar{I_2}\,(\cdot 2 + \cdot 0004\,N) = 550 - 2\,N \qquad \ldots \qquad (4)$$

$$\cdot 2\,I_2 = 550 - \bar{V_1} \qquad \ldots \qquad (5)$$

From these five equations the five unknown quantities are determined as follows :—

From (1) $\bar{I_2} = \cdot 75\, I_2$

Substituting in (4) and eliminating $N\,I_2$ from (2), (3) & (4)—

$\cdot 75\, I_2\,(\cdot 2 + \,0004\,N) = 550 - 2\,N$

and

$$100 - \cdot 2\,I_2 = 550 - 2\,N + \cdot 0004\,NI_2$$

$$\therefore 75 - \cdot 15\,I_2 - \cdot 0003\,NI_2 = \cdot 75\,(550 - 2N)$$

$$75 = 1\cdot 75\,(550 - 2N)$$

Hence, $N = 254$ nearest whole number.

Solving (4) for $\bar{I_2}$, we get $I_2 = 139$ amperes charging current.

$$I_2 = \frac{\bar{I_2}}{\cdot 75} = 185 \text{ amps. discharging current.}$$

From (3) $\bar{V_1} = 489$ volts—voltage when load is on and battery discharging.

From (5) $\bar{V_1} = 522\cdot 2$ volts when battery is charging.

The generator current when the load is on, is—

$500 - 185 = 315$ amps.

330. Mounting of the Glass Boxes:—The stands having been carefully erected on the supports, the glass boxes are unpacked and thoroughly cleaned, inside and outside, to remove every trace of packing material and dust. Each box should be carefully examined as to its soundness.

Next, the boxes with their insulators are placed on the bearers at the correct distances apart.

Setting of the Insulators :—Care must be taken to place the insulators exactly on the *centre line of the bearers*, and as near as possible to the vertical side of the box, which, at the same time, *should bear fully on all four insulators* To make sure that the box bears evenly upon all the insulators, pressure should be applied to the upper edge of the box, which will rock if it is unevenly supported.

All the boxes must be set up in such a way that *their upper edges are level, the sides of the boxes of the same row, in line, and the spaces between the boxes are as nearly equal as possible.*

331. First Charge of Battery :—Complete the circuits connecting the battery with the charging source and see the proper polarity and then put the electrolyte into the cells. The positive pole of the charging dynamo must be connected to the *positive* pole of the battery, *i.e., the brown plates* with fine ribs, and the negative pole of the dynamo to the negative pole of the battery, *i.e.*, to the *plates covered with sheet lead.* When all the cells are filled with pure brimstone sulphuric acid (1·180 sp. gr.), the charging should be commenced at once.

The voltage of the battery is then taken, and when the dynamo has been excited to give a slightly higher voltage than the battery, the charging circuit is closed; the machine is now regulated to give the permissible charging current, which should be $\frac{3}{4}$ths of the maximum charging current. *The battery must be charged at that rate for about 35 to 48* hours, with as little interruption as possible. The charging must be continuous for at least the first 12 hours, but it may be stopped, when afterwards necessary, as for instance during the night If a temporary stop has then to be made, no discharge must be taken from the cells. If this is absolutely impossible, the charge must be commenced and continued as long as possible, and resumed again after an interval not exceeding 10 hours. The gassing should be watched, and if any cells are not gassing or are not gassing as much as

the surrounding cells, they should be carefully examined and the cause of the trouble removed. The temperature of the electrolyte should be closely watched, and if it approaches 100° F., the charging rate must be reduced or the charging temporarily stopped until the temperature lowers. The specific gravity will fall rapidly after the electrolyte is added to the cells, and will then gradually rise as the charge progresses until it is again up to 1·215° or thereabout. As the charging progresses, the voltage of the battery rises, and the machine must be correspondingly regulated. If the charging dynamo will not give as much as $\frac{3}{4}$ths of the maximum permissible charging current of the battery, the duration of the charge must be correspondingly increased, so that the battery receives the same quantity of current (ampere-hours) as if it were charged with the full current.

After the battery has been charged for about 36 to 48 hours at $\frac{3}{4}$ths of the maximum rate, or for a longer period at a lower rate, the charge must be stopped and the battery must be completely disconnected both from the machine and the outside circuit, so that it can neither receive nor give current. The battery is allowed to remain in this condition of rest for one or, at most, two hours. It is then again charged with the same current as before until both the positive and negative plates give off gas freely, when the battery is again cut out and allowed to rest for an hour. Further charges and rests of an hour are then given alternately and this is continued until both kinds of plates gas freely as soon as the charge at the previous rate is switched on.

It is most important to see that both negative and positive plates gas freely, as under certain conditions gas may be given off on the positive (brown) plates only. It may, therefore, be misleading to judge only by the gas given off on the surface of the liquid. *It is the negative (grey) plates that must be specially watched.* During the periods of rest, the battery must, on no account, either receive or give off current.

As all the cells of a battery must be charged equally, no cell must be cut out by the regulating switch during

the first charge. For the same reason, in installations, where a double regulating switch is used, no lamps must be fed from the battery, as otherwise the main portion of the battery will receive less charging current than the regulating cells

Owing to the gassing, some of the acid in the cells is lost during the charge. This must be made up again, so that *the level of the liquid is always about half an inch above the plates.* The cells must not be filled to full. Further, care must be taken that the battery room is well-ventilated, so that the gases and fumes are readily drawn off. It is, however, scarcely possible to prevent moisture from depositing on the sides of the glass boxes and on the outer surface of the insulators. *The boxes and insulators must, therefore, be carefully wiped after the charge.*

It is advisable, during the whole of the first charge, to take readings at regular intervals of *the current and voltage*, as well as of *the specific gravity of the acid*, and to enter these readings in the log of the charge, which will be found among the forms which are sent with the battery.

The voltage of each cell at the end of charge will be between 2·5 and 2·7 volts. The charge cannot be considered complete until the specific gravity and voltage show *no rise over a period of four to five hours and gas is being freely given off from all the plates.* The positive plates will gas some time before the negatives. The specific gravity of the acid may rise above that at which it was put in. If the specific gravity of any of the cells at the completion of the charge is above 1·215°, allowance being made for the temperature correction, it should be adjusted to 1·215° sp. gr. by replacing some of the electrolytes in the cell with distilled water, but should it not rise to 1·215° in all the cells, additional acid of greater density than 1·215° should, on no account, be added, as subsequent charges should, and in all probability will bring it up to the full strength. After completion of charge and adjustment of specific gravity, the level of the electrolyte should be brought to ½-inch above the tops of the separators by the addition of 1·215° acid.

In cells equipped with board separators, a froth will form on to surface of the electrolyte during the initial charge. This should be skimmed off, from time to time, with a thin slip of wood.

After the completion of the first charge the battery is ready for working, and can be put into use. The cells should be charged as often as possible during the first fortnight, and an overcharge of one to two hours should be given each time for the first ten times (Tudor Battery).

The charging voltage must exceed that of the battery, which latter, during the operation, acts as a counter-E. M. F., the expression being $I—(V-e)/R$, in which I is the current, V the potential applied to battery terminals, e the counter-E. M. F., and R the internal resistance of the cell. Usually V is 5 to 10 per cent. greater than e, in order to cause the necessary charging current to flow through the resistance R of the cell.

In practice, V is regulated until the required charging current I is obtained.

332 Care After First Charge :—This affects the whole life. Do not discharge while it is not certain that the first charge is complete and do not discharge fully on the first occasion. Subsequent discharges for some time should be well within the limits of the battery and be followed by full charges in all cases. The full charge is shown by the evolution of large bubble of gas from both pipes.

333. Charging :—

General :—The battery should preferably be charged at normal rate.

The most approved method of charging lead cells is to give them a tapering charge starting the charges at a higher rate and gradually reducing the charge. The charging rate starts at one to two times the normal discharging rate and finishes at $\frac{1}{2}$ to $\frac{3}{4}$ of the normal discharge rate.

The charging rates are usually given by the makers, but in the absence of any instructions, they may be determined approximately by calculation, taking ·040 amperes per sq. inch of positive plate surface as normal. This can be checked after a few trials by the length of time

elapsing from beginning to the end charge, as evidenced by the voltage rising to 2·5 and vigorous evolution of gases, called "boiling." The eight-hour rate is usually taken as the normal in power station cells, and the five-hour rate in motor-car batteries.

The maximum charging rate is that at which the cell will absorb energy without heating more than 25 degrees F. above surrounding atmosphere, or excessive gassing. Usually this will be found to be not greater than the two-hour rate.

Do not charge at a lower rate than half the normal, nor at a higher rate than stated on the instruction sheet. It is important that *the battery should be given the proper amount of charge*, as indicated below, the *excessive charging must be avoided*, as not only will an unnecessarily rapid accumulation of sediment and excessive evaporation of the electrolyte result, but, what is more important, the life of the plates will be much shortened. The density of the electrolyte gradually rises during the charging operation, the density when charged being about ·025 higher than when discharged.

Ordinary or Regular Charges:—If the battery requires charging, the following procedure is recommended :—

(1) Take readings of the temperature and specific gravity of the acid in the "Pilot" cell. The *Pilot cell* is a special cell selected in a battery as an index to the condition of the whole. The battery is divided up into sections of from 30 to 50 cells, and one pilor chosen in each section. Take the reading of the dials of the discharge recording ampere hour meter (if installed). Work out from this how many ampere hours have been taken out of the battery since last charged, add 10 per cent. (one-tenth) to the number of ampere hours to be put into the battery on charge every ordinary or regular charge. Add this result (discharge in ampere hours plus one-tenth) to the reading shown on the dial of the charge meter, and charge until the dial reading on the charge meter reaches the calculated figure.

The charge may commence at the maximum continuous rate given, and even this rate should not be

continued after the cells commence to give off gas freely. From this point it is advisable to reduce the rate to half normal, as violent gassing (involving possible rupture of the positive active material), the scrubbing effect of the rush of gas bubbles, and dispersal of the acid as spray from the cells are thereby avoided.

During the charge note the behaviour of the cells at gassing point, observe if any are backward; if so, they should be closely examined, as the early gassing period of charge is the best time for detecting any weak cell by its appearance and behaviour.

334. Charging a Small Battery :—Low-voltage battery, say, from 2 to 12, and a current carrying capacity of from ½ to 20 amperes can be conveniently charged by opening up a single-wire either positive or negative of a circuit containing the required number of lamps. The connection is shown in the diagram; join

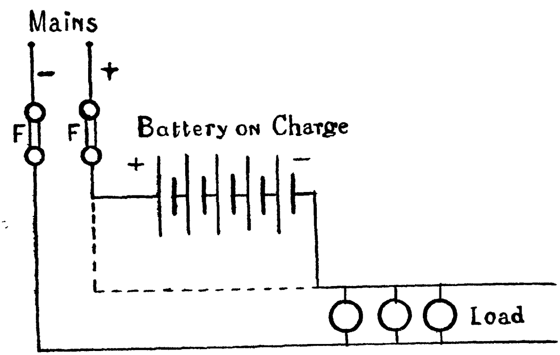


Fig. 6·08.

positive of the mains to the positive terminal of the battery. Take care that the load must be such as no excessive current should pass through the battery.

335. Directions for Charging Small Storage Batteries :—When there is only alternating current, it must be converted to direct current by means of

motor-generators, rotary converters, or mercury-vapour converters. Lamps or rheostats are used to vary the current. A 16-c. p., 110-volt, carbon-filament lamp has about 220 ohms resistance and will carry 0·5 ampere; a similar lamp of 32-c. p. rating has about 110 ohms resistance and will carry 1 amp. Take a suitable number of lamps in parallel to supply the charging current and charge the battery through the lamp. Charging current must always flow through the battery from the positive pole to the negative pole.

336. Conditions of Charge and Overcharge :— The battery should be charged at or as near the normal rate as possible until the following conditions are fulfilled :—

(*a*) The gravity of the Pilot cell having risen to a point which is 5 degrees (·005 sp. gr.) below the maximum, reached on the preceding "overcharge"; for instance, if the maximum reached on the preceding "overcharge" was 1·215°, the gravity to be reached on the "regular charge" is 1·210°.

(*b*) The voltage across the main battery having risen to a point which is ·05 to 0·10 volts per cell below what it was on the preceding "overcharge," the charging rate being the same in both the cases.

(*c*) The cells all gassing moderately.

Extended Charge or Overcharge :—An extended charge is one which is continued until all the indications of full charge are maintained for 45-60 minutes. These indications are :—

(1) Colour of the plates.

(2) Feel of the plates.

(3) Gassing of the cells.

(4) Maximum stationary voltage and maximum stationary specific gravity.

An extended charge should be given weekly if the battery is charged daily, or at least once a fortnight. If this rule is properly observed, abnormal or stubborn sulphation, which is the source from which nearly all the battery troubles arise, can be entirely averted.

The overcharge is complete when :—

(*a*) The gravity of the Pilot cell having reached a maximum, five successive 15-minute readings of this cell showing no further rise.

(*b*) The voltage across the main battery having reached a maximum ; five successive 15-minute readings showing no further rise, the charging rate being kept constant.

(*c*) The cells all gassing freely.

For a healthy battery in lighting and power service a safe working rule is to give 10 per cent. more charge in ampere hours than the amount taken out in the previous discharge, on all ordinary charges.

Every sixth or seventh charge, or in any case once a fortnight, the battery should be charged up irrespective of meter readings, until all the conditions of a full charge are attained.

If the battery is doing no work at all, it should still be given a freshening charge at least once a fortnight. The ampere-hour efficiency under such conditions cannot be calculated.

337. Specific Gravity :—The specific gravity of the electrolyte of a cell in good condition, when fully charged and at normal temperature of 60° F., should be between 1·205° and 1·215° Owing to loss through spraying towards the end of charges and to absorption by the sediment, the sp. gr. of the acid gradually falls away, the rapidity depending on the work, and care the battery receives. Unless a compensating hydrometer is used, allowance must be made for temperature variation on the rough basis of an increase of 1° specific gravity for each 3° F. decrease in temperature, and vice versa. For instance, electrolyte, that is, 1·215° at 60° F., will be 1·218° at 51° F., and 1·212° at 69° F. Above 60° F. subtract 1 point from the indicated valve.

338. Restoring Lowered Specific Gravity :— When, due to the above causes, the gravity of the electrolyte at the end of an overcharge and at normal temperature has fallen to 1·195°, it should be brought up to standard by the addition of 1·400° acid instead of

water, when topping up to replace evaporation. As it is of the utmost importance that acid should not be added unless it is first clearly determined that the falling away in sp. gr. is directly due to normal effects, *never, under any circumstance, add acid to a cell in which short circuits, high temperature, the use of unsuitable water, excessive charging, undercharging, or insufficient work may account for the low gravity.*

339. Compensating for Evaporation:—Preferably, distilled water should be used for topping up the cells. The water should be added carefully to avoid splashing. Rain water, under certain conditions, may be suitable for topping up purpose, but is most unsuitable where the installation is near the coast or near chemical works or large manufacturing towns. Hard water, water which has been softened, water from the drain pipes of steam engines, or from steam traps of boiler in which boiler compound is used, water from peaty districts, and the water from the mains of most towns, must be regarded as quite unsuitable for battery purposes.

340. Effects of Too Much Charging:—If the charge is unduly extended, work is being done, but it is useless, wasteful, and damaging to the plates.

Overcharging, *i.e.*, too much charging, if given at a low rate, produces active material in excess on the positive plates, and if given at a high rate, scrubs the formed material of the positive plates.

For, if the rate is not low enough to attack the positive, or high enough to scrub off the active material, the charge is breaking up the electrolyte by electrolysis, and each bubble of gas driven from the cells carries with it a film of acid.

In process of time acid is driven off by too much charging and the specific gravity of the acid is permanently weakened. Dilute sulphuric acid is sometimes to be added to compensate for this normal loss, but it should be done on expert advice only, as it is most important to be assured that the lowered specific gravity is not abnormal.

341. Effects of Insufficient Charging :—Too little charging will, for a time, give the battery an even higher efficiency than that guaranteed by the battery-makers, and give ground for gratification to the user until symptoms of reduced capacity arise.

An investigation shows lowered specific gravity, an unhealthy condition of the plates, and an abnormal accumulation of deposit in the cells.

342. Voltage at the End of Charge :—The voltage at the end of charge is not a fixed value, but will vary, due to several causes, namely, *the age of the battery*, the temperature of the electrolyte, and the charging rate; therefore, *a fixed voltage must not be considered when using the voltage method in determining the completion of charge*

When first installed, the voltage at the end of an "overcharge," with normal rate, will be from 2·55 to 2·65 volts per cell, with the temperature at 60° F.; but, as the age of the battery increases, this voltage gradually lowers until in some cases, with both the charging rate and temperature normal, it will have fallen to 2·40 volts per cell, or thereabouts.

The effect of changes in temperature on the final charging voltage is that it is noticeably lowered with an increase in the temperature above normal (60° F.) and correspondingly increased with lowered temperatures, irrespective of the age of battery.

Higher or lower rates than normal will, respectively, produce slightly higher or lower final charging voltages.

343. Voltage and Specific Gravity after Charge :—After the completion of a charge and the current is cut off, the voltage per cell will fall immediately to about 2·20 volts, and then quite rapidly to 2·05 volts, at which point it will remain while the battery continues on open circuit.

When the discharge is started, the voltage will at once fall to about 2·00 volts per cell or slightly under, depending on the rate.

Also, after the completion of a charge, particularly an "overcharge," the specific gravity of the electrolyte will rise slightly, due to the passing off of the gas bubbles formed during the charge ; for this reason all ot the Pilot cell gravity readings must be taken before the charging current is cut off.

344. **Discharging** :—The permissible rate of discharge depends upon the number of hours for which the discharge is required—the longer the time the smaller the rate. The product of rate into time is, however, not constant, but is greater with low rates of discharge than with high. Thus, in the Hart Accumulator, 25-plate lighting type, the rates of discharge for 5, 7 and 10 hours are 126, 99 and 75·6 amperes, respectively, giving discharge capacities of 630, 693 and 756 ampere-hours, The discharge rates for different times are always given by makers, and should never be exceeded, the ampere-hours taken out being recorded on the discharge *The normal discharge rate may be taken as equal to the normal charge rate*—usually taken as the eight-hour rate. The maximum discharge rate should usually be not greater than the one-hour rate except on short discharges followed immediately by charge, as on regulation work, in which case the cell may be worked as high as the 20-minute rate.

During discharging the E. M. F. of the cell falls rapidly to about 2 volts and then falls slowly to about 1 9 volts below which a further fall is not advisable. The charge then left in the accumulator is about 25 per cent. of the total capacity.

During the greater part of a complete discharge the drop in voltage is slight and very gradual, becoming greater with marked rapidity near the end. A storage battery *should never be discharged completely*, as it is then very likely to become sulphated or otherwise injured ; and moreover, the voltage falls so rapidly towards the end of discharge that the current would be of no practical value. The limit of discharge is usually considered to be the point at which the voltage drops to 1·75, though when cells are used at the one-hour rate the limit of discharge is 1·6.

A battery is not hurt by taking current from it at a high rate, but harm results from running a battery too low on discharge before re-charging it. Harmful results arise from leaving the battery idle, or giving it insufficient work. A battery requires exercise, its normal capacity falls, and it is liable to fall into a state of chronic sluggishness if it is not worked at all or only lightly.

A battery should never be allowed to stand in a discharged condition, but should be recharged immediately. The plates are practically free from attack if fully charged, and if the coating of active material on the positives is sufficiently dense, and if no impurities are introduced into the cells.

The charge usually left in a storage battery is from 10 to 30 per cent. of the total capacity, depending on the rate of discharge ; but this involves no considerable loss of energy or efficiency, since it remains in the battery each time, and the charging begins at that point.

345. **Readings** :— *It is important that readings should be regularly taken and recorded*, as follows :—

The specific gravity of the Pilot cell or the voltage across the main battery should be read and recorded just before the beginning and end of every charge, and also every hour during the charge.

On days when the battery is not charged, the gravity should be read and recorded at the usual time of starting the charge.

On the day of the "overcharge," at the same hour each time, a gravity reading of each cell in the battery should be taken before charge and recorded. *The gravity readings should be taken on open circuit.* On the same day, preferably just before the "overcharge," a voltage reading of each cell should be taken while a discharge is passing equal to the nine-hour rate of discharge. At the end of "overcharge" a voltage reading of each cell should again be taken and recorded while the charging current is still flowing.

The measurement of the voltage should always be made when the current is flowing in charging or discharging. *It is no use testing a cell for voltage on open*

circuit (*standing idle with no current passing because such readings have no value or meaning*). Since a low cell, no matter how low it may have been discharged, will show about 2·1 volts after standing on open circuit a short while. A weak cell will often give as high a reading as a healthy one on epen circuit.

After the "overcharge" a gravity reading of each cell on open circuit should again be taken and recorded.

There is a lag in the change of the density of the electrolyte, the acid not being absorbed or given off at once by the plates. Hence, a little time should be allowed before taking any hydrometer reading as final.

It is also advisable to agitate the electrolyte to ensure complete diffusion, as the electrolyte in the bottom of the cell is otherwise denser than at the top.

The cell readings should be carefully examined, and any cell showing a falling off in specific gravity or voltage, relative to the surrounding cells, should be noted, and *as soon as possible inspected and the cause removed.*

In addition to the above readings, the temperature of the Pilot cell should be read and recorded at least once each day, preferably at the end of charge.

All the readings should be logged on a form specially made for the purpose.

346. **Indications of the amount of charge** in a storage battery are to be inferred from the following :—

(1) Rise of voltage.
(2) Record of the ampere hours of charge and discharge.
(3) The density of the electrolyte.
(4) The condition of gassing.
(5) The colour of plates.
(6) The cadmium test.

* 347. **The Proper Condition of a New Battery** :—When the battery has received its first or initial charge on site, the plates are in a fully charged condition and ready to be put into active service. The

* E C. McKinnon.

plates should all have a thoroughly healthy colour—positives, rich chocolate; negatives, slight slate-hue—but they will feel more or less harsh and metallic. The smooth feel of a healthy plate will not mature until the battery has been at work some little time. The plates should all hang vertically and equidistantly from one another; the acid should be colourless, and free from smell. The level of the acid should be identical in each cell, and the specific gravity of the acid in no cell should vary more than two points plus or minus from the average of the whole battery. The connections should be re-made thoroughly tight after charge, and be covered with a coating of vaseline or an acidproof enamel.

348. **Inspection**:—*A careful inspection of each cell should be made periodically. This is very important, as it is bad practice to wait until trouble develops and then seek for the cause.* The most suitable time for an inspection is just before the "overcharge," so that if any trouble is discovered it can be removed in time for the cell to get the benefit of the "overcharge."

A careful examination should be made between the suspension lugs to see that they are in place and not touching, also anything unusual in the colour or appearance of the plates should be carefully noted. Note carefully if there is any short circuit. Short circuits should be removed with a thin strip of ebonite or wood (never use metal). Near the end of the "overcharge" all cells should be looked over to see that they are gassing freely. See that the accumulation of sediment in the bottom of the cells does not reach the plates.

349. **The following factors most closely influence the life of a battery:—**

I. (1) Absence of impurities, thus ensuring the avoidance of local action—internal discharge of the battery when the cells are not performing otherwise useful work.

(2) Sufficient work, to counteract the sluggish state into which an idle battery will fall.

(3) An adequate amount of charging:—

(a) At suitable rates;

(b) At an effective voltage;

(c) At sufficiently frequent intervals to reduce the sulphate normally set up on discharge, but which, if not reduced soon enough, attains a degree irresponsive to normal charging.

(4) Uniformity of capacity and efficiency throughout the battery.

(5) Sustained porosity of the plates, without which uniform working and high capacity are not obtainable.

II. The useful life of a battery is dependent from its earliest conception on:—

(1) Purity of materials.

(2) Suitability of plate design.

(3) Proper electro-chemical formation.

(4) Employment of electrolyte—acid and water—of certified purity.

(5) The use of no water other than distilled, to compensate for evaporation.

(6) Satisfactory initial charge.

(7) Sufficient work to maintain the plates healthy.

(8) Adequate charging at necessarily frequent intervals.

(9) Careful avoidance of exhaustive discharge and extravagant overcharges.

III. To these should be added:—

(a) Favourable temperature and atmospheric conditions.

(b) A well-illuminated battery room.

(c) General cleanliness.

(d) Effective insulation.

(e) Absolute freedom from internal short circuit.

(f) Removal of the deposit (waste products from the plates) before it silts up to the bottom edges of the plates.

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* The Storage Battery Management by H. C. McKinnon.

With strict but reasonable attention to the above points, none of which can be set up as detrimental to the satisfactory commercial employment of storage batteries, the battery will last a normal useful life, the termination of which will be based on the following :—

350. Life of Battery:—The positive plates will gradually wear by the slow conversion of the lead base—by charging—into lead peroxide, until the structure becomes too weak to bear its own weight, or insufficient to conduct the desired current, or until the capacity is below the requirements of the installation.

The active material of the negative plates will gradually harden or disintegrate, according to the type, and in time their capacity will fall so low that the negatives will be unduly exhausted on each discharge, which will react on the efficiency, and the extra charges required by the negative plates will adversely affect the more efficient positive plates increasing the rate of wear and tear on them.

The life of the positive plates is useful so long as the plates will hold together, are not distorted or stretched to an unworkable extent, and their capacity is not below the ordinary maximum demand of the installation.

The life of the negative plates is only useful so long as they yield the required capacity at an efficiency which will depreciate the positive plates by an undesirable amount of charging.

It is, therefore, false economy to fit new positive elements to cells in which the negative may look good for further useful work, but are deficient in efficiency.

It is also bad practice, theoretically, to renew a portion of a battery if the efficiency of the various portions will thereby be much dissimilar.

It is almost invariably fatal to the plates to partly replate a positive group of one cell or to increase the capacity of a battery by the addition of new plates to existing elements.

" Treatment can in itself altogether determine the life of any make of electrode, from the best to the worst, and as no two batteries, however well looked after, are ever served quite alike, it is impossible to set up any very rigid

standard of permissible depreciation; but for stationary batteries of fair size the rate of maintenance for periods up to ten years generally range from 5 to 10 per cent. of the selling price, although it is certain that the manufacturer must sometimes incur loss at the lower figure. The cost of maintaining a battery is practically that of renewing the plates, and these rates roughly correspond to an assumed life of three to six years for the positives and five to ten years for the negatives. "Life," in this connection, does not mean until the positives break down mechanically or the output of the battery becomes a negligible quantity, but is always limited to the period during which definite and reasonable percentage of the initial output can be obtained. Sometimes the full specified output has to be maintained, but more usually a decrease of 20 to 40 per cent. is allowed. (E. J. Wade).

351. Determination of Internal Resistance.—(1) Take an ammeter, a voltmeter and join as usual, note the terminal P. D. and the charge or discharge current. Open the circuit temporarily and read the voltmeter again as soon as possible, this gives the cell E. M. F.

$$\text{The internal resistance} = \frac{\text{E. M. F.} - \text{internal P. D.}}{\text{discharge current}}$$

$$\text{or, Internal resistance} = \frac{\text{terminal P. D.} - \text{E. M. F.}}{\text{charge current}}$$

This method is not very accurate.

(2) Use another cell in open circuit to balance the greater part of the voltage measured and take a millivoltmeter with a central zero—Fig. 6·09.

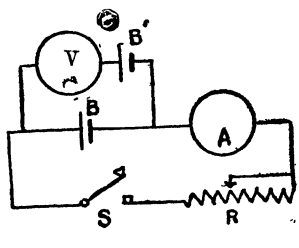

Fig. 6·09.
R=Change of V/I.

Another method is to obtain an adjustable balancing voltage by means of two cells and a side wire. The balancing voltage may be adjusted to exactly balance

the terminal P. D. on closed circuit, or to have a value intermediate between this and the E. M. F.

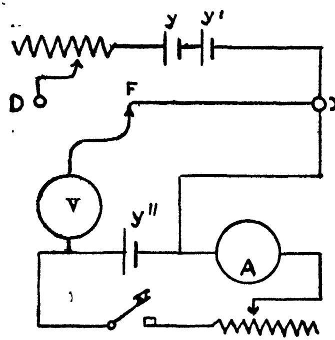

Fig. 6·10
R=Change of V/I.

(3) The most accurate method is to measure both voltages on the potentiometer, if the open circuit voltage has not time to change appreciably before balance is obtained.

Example 7.—The terminal P. D. of a cell when discharging at 15 amperes is 1·85 volts; on opening the circuit the voltage rises to 2·03 volts. What is the internal resistance of the cell?

If there is a possible error of ·03 volt in the readings (*i.e.*, about 1 per cent.), what are the possible errors in the value of the internal resistance?

Solution :—

The internal resistance = (2·03 − 1·85) /15 ohms = 0·012 ohm.

With possible errors of ·03 volt, maximum possible internal resistance = (2·06 − 1·82) /15 = 0·016 ohm.

If this is the true value, the error is − ·004 ohm, or − (·004/·016) × 100 per cent. = − 25 per cent.

Similarly, minimum possible internal resistance
= (2 − 1·88)/15 = 0·008 ohm.

If this is the true value, the error is ·004 ohm, or (·004/·008) × 100 per cent. = 50 per cent.

In each case the error expressed as a percentage of the calculated value is (·004/·012) × 100 per cent. = 33·33 per cent.

The actual error is not likely to be more than a third of the above values, say, about 11 per cent. of calculated value.

*** 352. Electro-motive Force and its Variation**—The open-circuit electro-motive force of a storage cell is dependent on :—

(1) Density of the electrolyte.
(2) Temperature.
(3) Character of active material.

The potential difference at the terminals of a cell is dependent on these factors, and also on :—

(4) Rate of current flow.
(5) State of charge of the cell.
(6) Internal resistance.

The electro-motive force increases with increase in concentration.

The electro-motive force at various electrolyte densities may be calculated by the following formula :—

$E=1{\cdot}850+0{\cdot}917\ (S-s)$;
$E=$ Electro-motive force in volts ;
$S=$ Specific gravity of electrolyte ;
$s=$ Specific gravity of water ;

the two specific gravities being taken at the temperature of observation.

This formula may also be written :—

$$E=1{\cdot}850+0{\cdot}00057\ z,$$

where $z=$ grams of H_2SO_4 per liter of electrolyte.

These formulas do not hold for the extremes of concentration—zero or 100 per cent.—but are correct for densities of from 1·050 to 1·650.

353. Description of Cadmium for Battery Testing.—A small piece of cadmium, say, 5/8 by 5/8 by 1/32 inch, is placed in a perforated hard rubber casing. The conducting wire is put in a rubber sleeve and wax is used to protect the soldered joint of copper and cadmium. Cadmium electro-positive to lead peroxide and electro-negative to spongy lead. To sulphated positive or negative plate cadmium is electro-positive, but less so than to a fully charged positive plate.

* Lamar Lyndon's Storage Battery Engineering.

Under normal conditions *when fully charged* and in open circuit, the difference of potential between the positive and the cadmium piece immersed in the liquid is 2·5 volts or nearly so, and between the cadmium and the negative plates is zero or nearly so It is sufficient if the sum of the readings is about 2·5 volts.

354. Use of the Tester:—Insert the tester at the centre of the cell to get a uniform current distribution. This test gives readings the sum of which is less than 2·5 volts, when hydrometer tests, temperature, and charge data show that the cell is not fully charged. If these and other data show that the charge is to be completed, and the cadmium test gives ·1 volt or more below 2·5 volts one or more plates are defective and may be found by individual cadmium readings. A cell in which all the other conditions tend to show full charge, but the potential difference is low, a cadmium test is made; and the set of plates which shows the falling off from normal reading is the defective one, and should be examined for some of the troubles.

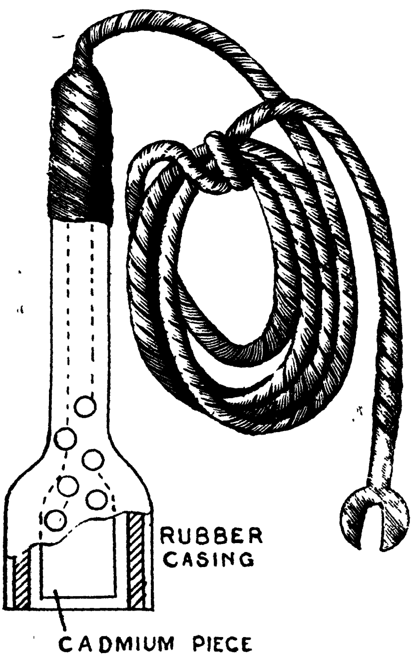

Fig. 6·11.

If the reading to the positive plates is less than 2·45 V, the positive plate is not fully charged. If the reading

to the negative plate is less than 0·23 *V* or in the reverse direction, the negative plate is not fully charged.

Precaution :—In some cases the cadmium reading with respect to both positive and negative plates may approach zero; this is caused by a short circuit in the cell, which should be found and removed immediately.

355. Preservation of the Cadmium Tester :—Keep the cadmium tester in a beaker of distilled water when not in use as it is advisable to have the cadmium wet before the test is made, for otherwise the readings increase when cadmium is first placed in the electrolyte. All foreign matter should be carefully removed from the cadmium, as it might affect the results. If gas bubbles collect on the cadmium, they should be taken off, as they tend to lower the readings.

Example 8.—

Cadmium to positive ..	...	2·0
Cadmium to negative ...	...	0·2
Cell voltage	...	1·8

Cell fully discharged.

Cadmium to positive ...	...	2·0
Cadmium to negative ...	...	2·3
Cell voltage	...	−0·3

Cell reversed, negative exhausted.

Cadmium to positive ...	...	0·18
Cadmium to negative ...	...	0·20
Cell voltage	...	−0·02

Cell reversed, positive plate exhausted.

In this case when testing the negative plate the cadmium must be connected to the positive terminal of the voltmeter, if a central reading voltmeter is not available.

356. Cadmium Test :—The capacity of a cell is measured in ampere-hours, and is the quantity of electricity which is given out during a single discharge. The

energy output or watt-hours is the product obtained by multiplying the ampere-hour output by the average voltage of discharge. It is limited by the capacity of the positive plates. The capacity of a battery, theoretically, is that of the weakest cell it contains.

The term "*capacity*" refers to the amount of energy which may be taken out of a cell from the beginning of discharge until the gradually-diminishing electro-motive force reaches some value which has been arbitrarily fixed and which is reached long before all of the active material is reduced to $PbSo_4$, and zero voltage attained.

1·80 volts is the potential which has been adopted as the stopping point of discharge when the battery is supplying current at the 8-hour rate, or 1·68 volts when supplying current at the 1-hour rate. The terminal voltage, *i.e.*, the voltage at which the battery is assumed to be completely discharged for any rate, may be computed from the formula :—

$$E = 1{\cdot}66 \times 0{\cdot}0175\ T,$$

in which T is the time in hours during which the discharge lasts. Thus, the final voltage for a cell at the 4-hour rate would be $1{\cdot}66 + 0{\cdot}0175 \times 4 = 1{\cdot}75$ volts.

For stationary batteries a capacity of two to three amp.-hrs. per lb. is usual.

With the standard 8 hours discharge rate and a temperature of 60° F. the American practice is to count 40 to 60 amp.-hours per square foot of positive plate surface-No. of positive plates in parallel × length × breadth × 2.

357. For Electric Automobiles :—The limit is about 5 ampere-hours per lb. per cell. With plates of ordinary thickness the capacity is roughly ½ ampere-hour per sq. in. of plate area (only one side is taken in reckoning the area).

The capacity obtainable from electrodes ranges from 40 to 75 ampere-hours per sq. foot of positive plate (both sides included), depending on the type, density of the electrolyte, and other conditions. The capacity of Plante' plates is from 40 to 60 ampere-hours per sq. foot of positive surface, depending on the depth of the formation and the type of plate, while pasted plates will

yield from 50 to 75 ampere-hours per square foot, depending on the thickness and porosity of the active material. Count ·026 ampere per sq. inch of surface in charging and ·029 ampere per sq. inch in discharging as the maximum allowed by the makers.

358. The factors on which the capacity depends are :—

(1) Character of active materials.
(2) Porosity of active materials.
(3) Disposition of active materials.
(4) Quantity of electrolyte.
(5) Density of electrolyte.
(6) Rate of diffusion of electrolyte.
(7) Temperature of electrolyte.
(8) Rate of discharge of electrolyte.

If the capacity of a storage battery is C_8 amp.-hr. when discharged at the 8-hour rate, its capacity is greatly decreased if it is discharged at greater rates. If the current is such that the voltage per cell falls to 1·8 volts in 1 hour, the current is said to be 1-hr. rate and the capacity falls to $\frac{1}{2}$ C_8 amp.-hr.

The relation between discharge rate (n) and the corresponding capacity in amp.-hr. is given approximately by the formula

$$C_n = (C_8/2) \sqrt[3]{n}.$$

If I_0 is the current corresponding to the 8-hour rate and i_n the current corresponding to the (n) hour rate, we have $C_8 = 8\ i_8$ and $C_n = n\ i_n$; whence substituting the above approximate relation between C_n and C_8, it follows that $i_n = 4\ i_8/\sqrt[3]{n^2}$ (nearly).

359. The decrease in capacity at higher rates of discharge is due to :—

(1) Electrolyte is not being able to circulate as rapidly as required, thus diluting the acid in the pores of the plates before fresh acid can take its place.

(2) A layer of lead sulphate is formed on the surface of the plate preventing further action.

In four plates from 3/32" to 5/32" in thickness, about 50 ampere-hours per pound of active material, or 25 ampere-hours per pound of plate can be obtained. In

the more substantial type, say, from $\frac{3}{4}''$ to $\frac{1}{4}''$ thickness, about 30 ampere-hours per lb. of active material and from 12 to 20 ampere-hours per lb. of plate are about the average.

Usually, more positive active material than negative is provided.

Stationary batteries are rated on the basis of 8 hours, batteries on electrical automobiles on the discharge basis of a four-hour discharge. Electrical batteries used in the electric railway sub-stations are usually rated on the one hour's discharge.

For Edison cell the ampere-hour capacity is practically the same at all rates of discharge, their current rating is regularly based on discharging in 5 hours, *i.e.*, the ampere-hour capacity divided by 5.

360. Efficiency:—The efficiency of a battery is the ratio of the useful current or energy given out on discharge to that put into it on charge. The *ampere-hour efficiency* is the useful discharge in ampere-hours, divided by the number of ampere-hours input on charge, and the *watt-hour efficiency* is the ratio of watt-hours output to watt-hours input.

The work absorbed or given out by a battery is measured in watts, and only the energy or watt-efficiency is of value to the engineer.

361. The efficiency of a battery depends on:—

(1) The charging rate.
(2) The discharge rate.
(3) The virtual internal resistance.
(4) Thickness and porosity of active material
(5) Density, quantity and diffusion of electrolyte.
(6) Length of time elapsing between end of discharge and beginning of next charge.
(7) Freedom from local action.
(8) Temperature.

The energy losses in a storage cell which tend to reduce its efficiency are (1) the I^2R, or resistance loss; (2) local action, or internal discharge; (3) evolution of gas at the end of discharge; (4) irreversible chemical reactions.

The Volt Efficiency

$$=\frac{\text{average voltage on discharge}}{\text{average voltage on charge}}.$$

$$=\frac{Eb-IR}{Eb+IR}$$

is called the volt efficiency and is lower the larger the current I, that is, the higher the rate of charge and discharge. At the normal rates of charge and discharge this efficiency is seldom less than 80 per cent.

The ampere-hour or quantity efficiency of the battery

$$=\frac{\text{ampere-hours output}}{\text{ampere-hours input to recharge}}$$

Watt-hour or Energy Efficiency

$$=\frac{\text{watt-hours output}}{\text{watt-hours input to recharge}}$$

$$=\frac{\text{amp.-hours output} \times \text{average discharge voltage}}{\text{amp.-hours input} \times \text{average charging voltage}}$$

$=$amp.-hour efficiency $\times$ volt efficiency,

both of which quantities are lower, the higher the rate of charge and discharge.

Example 9.— A battery has a discharging E M.F. of 2·2 volts per cell at start, and gradually falls to 1·83 volts at the end of discharge. If the internal resistance of the leads from the cells to the lamps be ·011 ohm, what number of cells must be used (*a*) at the commencement and (*b*) at the end of discharge, if they supply current to 200 20-watt 220-volt lamps ?

Solution :—

Current taken by the lamps

$$=I=\frac{20\times 200}{220}$$

$$=18{\cdot}1818$$

Terminal E. M. F. of each cell$=$E. M. F. on open circuit, or where r=resistance of each cell.

Volts drop in leads $= \cdot 01 \times 18\cdot 1818 = \cdot 19$, say, $\cdot 2$.

$\therefore$ the battery has to supply current at a pressure of $220 + \cdot 2 = 220\cdot 2$ volts.

$$\therefore \text{ number of cells} = \frac{220\cdot 2}{\text{terminal E. M. F. of each cell}}$$

$$\text{Cells at the commencement of discharge} = \frac{220\cdot 2}{2\cdot 2 - I_r}$$

$$= \frac{220\cdot 2}{2\cdot 2 - 18\ 1818 \times \cdot 0003} = 105 \text{ cells.}$$

$$\text{and cells at the end of discharge} = \frac{220 + \cdot 2}{1\cdot 83 - 18\cdot 1811 \times \cdot 0003}$$

$$= 121 \text{ cells.}$$

Thus the number of end-regulating cells must be $121 - 105 = 16$.

Example 10. A battery of 120 accumulators is charged with a constant current of 80 amperes for 8 hours, the average E. M. F. required to charge each cell being 2·3 volts. The battery is afterwards discharged 100 amperes for 6 hours, the average discharge E. M. F. being 2 volts per cell. Determine (1) the quantity efficiency, and (2) the energy efficiency.

Solution :—

$$\text{(1) Quantity efficiency} = \frac{\text{ampere-hours output}}{\text{ampere-hours input}}$$

Ampere-hours output $= 120 \times 100 \times 6$
Ampere-hours input $= 120 \times 80 \times 8$

$$\therefore \text{ quantity efficiency} = \frac{120 \times 100 \times 6}{120 \times 80 \times 8} = \cdot 937$$

or, 93·7 per cent.

$$\text{(2) Energy efficiency} = \frac{\text{watt-hours output}}{\text{watt-hours input}}$$

$$= \frac{110 \times 100 \times 6 \times 2}{110 \times 80 \times 8 \times 2\cdot 3} = \cdot 815$$

or, 81·5 per cent.

In ordinary service, portable Edison batteries have a watt-hour efficiency of 40 to 50 per cent. and portable lead batteries 65 to 75 per cent. The ampere-hour efficiencies of the same batteries are 60 to 70 per cent. for Edison and 80 to 90 per cent. for lead batteries in very heavy loads, the watt-hour efficiency drops even lower than the lowest values given, and on very slow discharge rate it rises even higher than the high value.

362. Uniform Capacity and Efficiency throughout the Battery:—If new positives are fitted to old negatives it is highly probable that the negatives are so much reduced in efficiency that they will require more charging than the positives, which are consequently overcharged, and the wear and tear on them is abnormal until the negatives are renewed.

If new negatives are fitted to old positives, the latter are liable to be overworked and deteriorate at a rapid rate.

Briefly explained, it is understood that at, say, the ten-hour rate of discharge, the capacity of a cell is the amount obtained before the cell falls to 1·83 volts.

The capacity of a battery theoretically is that of the weakest cell it contains.

***363. The durability of battery electrodes is dependent on—**

(1) Character of ...
(2) Adhesiveness to supporting grid of
(3) Means for holding to grid of (pasted plates) ...
(4) Thickness of layer of ...
(5) Porosity of ...
(6) Distribution over supporting plate surface of ...

} Active material.

(7) Density ...
(8) Quantity ...
(9) Purity ...

} of electrolyte.

* Lahmar Lyndon's Secondary Battery Engineering.

* E. C. McKinnon's Storage Battery Management.

(10) Rate of charge per unit of plate area.
(11) Rate of discharge per unit of plate area.
(12) Duration of maximum rates.
(13) Maximum voltage to which cells are charged.
(14) Minimum voltage to which cells are allowed to discharge.
(15) Time elapsing between the cycles of charge and discharge.
(16) Maximum temperature at which cells are operated.
(17) Maximum length of time cells is permitted to stand idle in electrolyte.
(18) Efficiency of separation between plates.
(19) Freedom from conditions favourable to local action.
(20) Location with reference to gases which might be absorbed in the electrolyte and prove injurious to the plates.
(21) Amount of available base leads on the peroxide elements which may be converted into active material (in Plante plates).

364. I. The **factors which set up abnormal working** may be classified without order of importance, as follows:—

(1) Unsatisfactory design.
(2) Unsuitable moulds.
(3) Careless manufacture.
(4) Impure materials.
(5) Unsatisfactory initial charge.
(6) Charging in wrong direction.
(7) Impure electrolyte.
(8) Using impure water to compensate for evaporation.
(9) Failure to work the battery into normal stable condition when new.
(10) Too much charging.
(11) Charging at too high rates.
(12) Charging at too low rates.
(13) Insufficient charging.
(14) Running the battery too low on discharge.
(15) Leaving the battery in a discharged condition.

(16) Recharging at too remote periods.
(17) Failure to keep the plates covered with electrolyte.
(18) Unwarranted addition of acid.
(19) Internal short circuits.
(20) Omitting to clean out cells when necessary.
(21) Abnormal temperatures.
(22) Unsuitable environment.
(23) Inaccurate instruments.
(24) Cells in series dissimilar in efficiency or capacity, or both.
(25) Positive and negative groups in the same cell dissimilar in efficiency or capacity, or both.
(26) Working old and new positives in the same cell.
(27) Unsuitable separators.

II. **What to Guard Against to obtain the Longest Life from the Battery.**—The chief points are the following :—

Failing to give the battery a proper initial charge.
Failing to give a new battery plenty of work and liberal charging.
Charging the battery too little.
Charging the battery too much.
Working the battery too little.
Running the battery too low in voltage and specific gravity of the amount of work done.
Charging the battery at too high rates, especially towards completion of charge
Charging the battery at too low rates (less than half the normal).
Allowing the sediment to reach the bottom edges of the plates before having it removed.
Having the battery room too hot, or letting too strong a breeze blow through the room, both of which cause an increase in the rate of evaporation.
Using unsuitable water to compensate for evaporation.
Not adding water sufficiently often to always keep the plates covered with electrolyte.

Adding an acid unwarranted by the condition of the plates or working conditions.

Using acid unsuitable in strength or purity.

Neglecting to observe the indications of irregular treatment.

Neglecting to attend to weak cells promptly.

Failing to clear internal short circuits.

Allowing individual cells to be thoroughly exhausted (volts run down to zero).

Allowing individual exhausted cells to receive charge in the wrong direction, by leaving them joined up in series with the rest of the cells on discharge

In bolted-up batteries, allowing the connections to become dirty, corroded or slack (which sets up heating and melting of the lead lugs).

Having the regulating switch discharge lever across a greater number of cells than that across the charge lever, during simultaneous charging and discharging.

III. **Sources of Primary Troubles** :—The chief primary troubles arise from :—

(1) **Too Much Charging** :—The effects of too much charging are progressive—

(*a*) The expander is dispelled from the plates or exerts an undue distending effect on to the active material which, in turn, puts an undue pressure on the lead gauze, and may force the gauze outwards, or be "paid" out through the perforations.

(*b*) The excessive amount of charging in time causes the electrolytic lead in the active material to contract.

(*c*) The active material in contracting settles down as a non-porous inefficient mass in each individual case

This may give rise to **secondary troubles**. Alternatively :—

(*d*) Through contraction, the active materiall loses intimate contact with the containing metal work and the plate becomes subject to secondary troubles.

Too much charging also produces an excess of spongy lead. A slight formation of spongy lead on the exterior of the plates is a healthy sign, but any large amount is a source of trouble, and box negatives, owing to their design, lend themselves to the accumulation of spongy lead growth more readily than smooth-faced plates.

Spongy lead is produced electrolytically in a storage cell by the action of the charging current on fine particles of lead-dust, peroxide or sulphate, in contact with the negative element.

The presence of spongy lead in a cell is a potential source of troubles.

(2) **Too Little Charging** :—The sequence of effects of too little charging is :—

(*a*) The active material of the negative, normally sulphated on discharge in ratio to the amount taken out, measured in ampere-hours, is not properly desulphated on the following charge.

(*b*) The capacity of negatives is thereby reduced, and the plates are liable to be run down too low on discharge.

(*c*) The sulphating increases, the plates fall lower and lower in capacity, and the sulphated material becomes non-conducting and non-adhesive.

This condition introduces further troubles.

(3) **Insufficient Work** :—Insufficient work sets up a state of sluggishness which is liable to develop on the following lines:—

(*a*) The outer portion only of the active material is worked, and strong acid is produced on charge in the inner pores of the material.

(*b*) This sets up sulphating, which in time attains the malignant condition non-responsive to charging, either ordinary or special, under service conditions.

(*c*) At the same time the capacity of the plate is reduced to that of the active material still unaffected.

This introduces the possibility of further troubles.

(4) **Running the Battery too low on Discharge** :—The effects from this cause follow in sequence :—

(*a*) First the negative is sulphated too densely on each discharge.

(*b*) In this condition it is less responsive to normal charging currents, and is less efficient.

(*c*) The capacity in consequence gradually decreases until a stage is reached when secondary troubles inevitably occur.

(5) **Introduction of Impurities into the Electrolyte** :—This is a trouble just as easily avoided as all the others enumerated, if only the makers' instructions be worked to, reasonably closely.

The action of impurities on the negative plates is usually less destructive, but more active than on the positive plates.

The primary effect of impurities, either directly by the use of impure materials or electrolyte, or indirectly by impurities introduced in the water added from time to time to compensate for evaporation, is local action—the self-discharge of the plates, or internal circuits through which current is passing in the cells—whether the battery is doing useful external work or not.

On long continuous or intermittent discharges, or during long idle periods between charges, the local action may be sufficient to exhaust the cells containing the impurities. This gives an opening for secondary troubles.

Test for Impurities

Hydrochloric Acid (*Chlorine*) :—To a small quantity of dilute electrolyte add a few drops of nitric acid, then add 3 drops of silver nitrate. The formation of a white, cloudy precipitate indicates the presence of chlorine in some form.

Nitric Acid :—Mix a solution of diphenylamine in concentrated sulphuric acid, and add it to the sample under test. Nitric acid will be indicated by a blue colour

Iron :—Fill a test-tube with dilute electrolyte and heat to boiling point ; add several drops of concentrated

nitric acid and boil again. Repeat two or three times. When solution is cold, add a few drops of potassium sulphocyanide, which will colour a deep red if iron is present.

Copper :—Add common ammonia until the resultant mixture gives an alkaline reaction ; deep blue indicates the presence of copper.

Arsenic :—Add an equal quantity of hydrogen sulphide solution ; a yellow precipitate indicates arsenic.

(6) **Working the Cells in too weak Electrolyte** :—This will primarily affect the capacity of the plates if towards the end of discharge there is insufficient acid to give the necessary chemical combination with the active matter in the plates. In addition, the very weak electrolyte at the end of discharge tends to convert the active material into hydrate of lead, which is difficult to reduce on charge.

***365. The Principal Diseases to which a Battery is subject are** :—

(1) Loss of capacity.
(2) Corrosion of plates.
(3) Fracture and buckling.
(4) Shedding of active material.
(5) Sulphation
(6) Reversal of negative plates.
(7) Internal discharge or local action.
(8) Premature gassing.
(9) Loss of voltage or low cells.
(10) Softening of peroxide (on pasted positive plates).
(11) Dry plates.

(1) LOSS OF CAPACITY :—As distinguished from loss of charge—may arise from (*a*) clogging of pores of the lead sponge with sulphate or impurities ; (*b*) contraction of the pores of the mass ; (*c*) loss of active material from the grid ; (*d*) formation of a layer of sulphate between the grid and the active material ; (*e*) loss of electrolyte.

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When the negative plate shows a decreased capacity and exhibits no sign of sulphation or loss of material, it will generally be found that the material has shrunken, or the pores are clogged with sulphate and impurities.

The rejuvenation of these plates is accomplished by charging the battery, removing the negative elements, placing them in a bath of sulphuric acid as cold as possible and having a density of 1·240. They are connected as anodes, or in a reverse manner to that in which they are normally connected. As cathodes "dummy" plates of plain sheet lead about 1/16 inch thick are used. On passing current through the active material it is completely peroxidised, the current is again reversed, the acid in the bath first being removed and fresh acid substituted in order that the impurities may not be redeposited on the negative plates. When the elements are finally converted back into sponge-lead and reassembled with the positives, it will be found that the capacity and activity of the battery are increased and brought up to nearly their original condition. Reversal of the complete battery—both positives and negatives—should be avoided if dummies can possibly be secured. If not, however, and the reversing be carefully done, possibly no harm will result to the positive plates.

(2) CORROSION OF PLATES:—It may occur from two causes—(*a*) the chemical action resulting from electrolytic decomposition of highly dilute acid in the pores of the active material, and (*b*) the presence of lead-dissolving acids or their salts in the eletcrolyte.

The first condition cannot be remedied, as it occurs in every cell if the discharge be pushed too far, or if the plates have a thick layer of active material when the rate of discharge is high. If the electrolyte contains lead-dissolving acids, their presence will be manifested by a continuous increase of capacity, which means that the forming process still goes on attacking the plates. The obvious remedy is to change electrolyte, and substitute fresh acid, free from injurious substances. In addition to these effects, there is the normal slow disintegration due to the action of the acid and products of decomposition, which cannot be completely stopped,

as it is the natural depreciation to which plates are subject. It can be partly remedied, however, by decreasing the density of the electrolyte. The density for positive plates is 1·230, and for negatives is 1·190 (approx.); 1·210 to 1·220 is the usual density, being a compromise between the two.

All corrosive actions of liquids on solid substances immersed in them take place with greatest rapidity at the surface of the liquid, and the portions of the battery plates, which emerge from the electrolyte, may disintegrate at the surface of the acid before the submerged portions have greatly depreciated. This can be rendered of small importance by keeping the plates always completely covered with liquid, and making the lugs which pass from the plates out to the terminals, of thick dense lead.

(3) SHEDDING OF ACTIVE MATERIAL cannot be prevented if it be improperly formed or applied and not of such a character that it easily disintegrates or loosens from the grid. Shedding occurs with good active material, however, to a limited extent, and this is due to expansion and contraction, which the grid cannot follow, or to the rapid release of gases when charging is done at high rates and the plates are overcharged. When shedding takes place in a greater degree than ordinary usage and depreciation call for, the following rules should be observed :—

Charge at lower rates ; do not overcharge, *i.e.*, do not go about 2·4 volts ; do not discharge down too far, say, below 1·8 volts. Pasted plates should not be charged after gassing begins, except on a monthly overcharge.

(4) BUCKLING AND FRACTURE :—Buckling and fracture of the positive plates is one of the commonest battery troubles.

CAUSE :—Buckling and fracture are due to unequal expansion and may be caused by charging at too high a rate, by charging too much, especially at very low rates, by running the battery too low on discharge, or by leaving the battery too long in a discharged condition and also by insufficient charging. Batteries, which are discharged at a high temperature, may buckle. It

sometimes arises from defective plates when there is no remedy. It is sometimes due to exposure to light, the convex side being always away from the light. Plates which have buckled through sulphation strains will be hard and brittle, while far too much charging at low rates will be accompanied by a very rich colour of the plates and tendency for the plates to be of almost the consistency of gingerbread. Both causes give aggravated effects if impurities are present in the electrolyte. It must surely be appreciated, therefore, that buckling can, to a large extent, be avoided by careful attention to the proper instructions.

TREATMENT OF BUCKLED POSITIVES:—Buckled positives, which are very harsh and brittle through sulphation, should be softened, as far as possible, by prolonged charging at very low rates (not exceeding half the normal). Only after this has been done can straightening be effected with any degree of success. Positives, which appear healthy as regards colour and feel, but are buckled, should be straightened when in a fully charged condition. The straightening should be done by fitting packing boards of the correct thickness between the positive plates and subjecting the whole group to pressure in a hand screw-press. It is advisable to well scrub the straightened plates with a hard brush to remove any excess active material in order to afford room for future expansion. If it is found that the plates are too hard or brittle to straighten without breaking, no further attempts should be made. The plates should be reassembled in their box or cell, and the positives and negatives should be kept apart by inserting glass strips about ½ in. wide, made of 15 oz. or 21 oz. glass at points of probable contact. No chemical should ever be added to cells to soften sulphated positives which are buckled.

In case of defective plates, keep the electrolyte circulating, refrain from discharging too far and keep excluded from light and heat.

(5) SULPHATE :—There are two distinct grades of sulphation, one normal and the other abnormal.

During the ordinary discharge sulphating takes place which is entirely normal being a combination of the acid

with the active materials of the plates producing an electric current.

CAUSE:—Sulphating is caused by (1) overdischarging; (2) by leaving discharged for a considerable time; (3) by having too strong an electrolyte. If the battery is not worked sufficiently, especially if new, the lead is very susceptible to be attacked by the acid, and in time abnormal sulphation results—the plates become light in colour, feel hard and metallic, lose their porosity, and consequently some of their capacity which is dependent on porosity. Abnormally sulphated plates are extremely difficult to fully charge. Abnormal sulphate destroys the texture or nature of the negative active material and damages the positives by causing an increase in bulk which sets up irregular strains on the plates.

TREATMENT OF SULPHATED PLATES:—Sulphated plates include positives and negatives. The remedy in both the cases is *prolonged charging at low rates.* The charge may commence at half the normal rate, but as soon as free gassing takes place, the rate should be gradually lowered to quarter the normal, not less. The benefit derived from the charging is increased by making the final stages intermittent with pauses or rests of one hour's duration. The first hour's rest may be given when the cells appear to be absolutely fully charged, judged by the healthy colour of the plates and constant voltage of the cells and constant specific gravity of the acid. When the current is again switched on, however, no gassing takes place immediately, or possibly for some little time, and this shows that the plates are absorbing the current advantageously. When the former point of apparent full charge has again been attained, second pause or rest may be made. These pauses and charges should be repeated until the plates commence to gas freely as soon as the charging current is switched on at quarter the normal rate. It is important not to be deceived by the appearance of positives which may seem to be sulphated on the surface, but, when brushed, this may be found to be a loose surface powder which masks a healthy surface beneath. It would be a waste of current to try and remove this powder by charging.

The alternatives are to brush it off or dislodge it by discharging at heavy rates. It is not advisable to try experiments for the removal of sulphate by adding chemicals to the acid. It will be found very beneficial to reduce the specific gravity of the acid to 1·050° before the prolonged charge, when dealing with badly sulphated plates.

Carbonate of soda added to the electrolyte has a beneficial effect in preventing sulphating. Sometimes an electrolyte made up of water 19 parts, strong acid 5 parts and soda solution (12 fluid ounces of strong acid to one quart of saturated solution of carbonate of soda) 1 part.

(6) REVERSAL OF NEGATIVE PLATES occurs when there are several cells in series with each other with or some external electro-motive force, and, is occasioned by complete discharge down to zero and continued charge in a reverse direction with a consequent reversal of the plates.

This seldom happens, however, except in cases where a cell loses its capacity through some accident or defect and its discharge is ended before the other cells in series with it have been completely discharged. The large capacity cells overpower the defective cells and reverse it.

TREATMENT :—Continue the charge until the cell is brought fully up to its normal condition. The cause of the capacity loss should be ascertained and corrected, otherwise the reversal will again take place on the next discharge.

(7) LOCAL ACTION :—This is the term applied to the self-discharge of the plates when the cell containing them is not doing any useful work. In batteries which have been in use for some years, the negative plates are sometimes found to gas freely on open circuit. This indicates that local action is taking place, due, in all probability, through contamination of the electrolyte. If the plates of one cell gas very freely on charge before any other cells show signs of gassing, this is a sign usually of weak negatives due to bad sulphation or local action.

(8) PREMATURE GASSING :—It is sometimes found that the negative plates commence to give off gas freely on

charge before the amount taken out on the previous discharge has been put back, or alternatively odd cells in a battery give off gas very freely long before the remainder. This is due to the negative plates being low in capacity either through length of service or through unhealthy condition. In the former there is no means of recovery, but if the negatives are low in capacity through bad sulphation, or owing to the negative active material having become hard through contraction, it is sometimes possible to effect recovery by prolonged charging at very slow rates. As premature gassing is noted, the rate of charge should be reduced to a point where the gassing ceases.

(9) LOW CELLS:—*Falling off in specific gravity or voltage* relative to the surrounding cells.

Lack or deficiency of gassing on overcharge as compared with surrounding cells.

Colour of plates appreciably different from those in surrounding cells.

In case of any of the above symptoms being noticed in a cell, examine carefully for the cause and remove it at once.

TREATMENT:—The above symptoms in a cell indicate that it has fallen away from the rest in its state of charge. If the cause is discovered and removed immediately, it will usually be restored to normal condition by the following "overcharge." If then only partially restored, it must be carefully watched during the ensuing week. If the next "overcharge" does not completely restore it, or if the original deficiency was very great, it may be necessary to give it a separate charge.

SEPARATE CHARGING:—(1) Give the battery a special "overcharge," but care should be taken not to carry this to excess. (2) Cut the low cell out of circuit, for several discharges, coupling it again just before beginning the following charges. This method is specially applicable where the elements are bolted together. (3) Give an individual charge while the battery is either on discharge or standing idle. The charge can be given either from the charging generator or booster through a water resistance or from a small milking booster or dynamo, usually

motor-driven. This method is specially applicable for batteries in which the connections are burnt up solid. Before putting a cell that has been low, back into service, care should be taken that the cell has been fully charged. This should be determined by continuing the charge until five successive hourly readings of the gravity and voltage show no change, and at the same time the plates gas freely and are of normal colour.

(10) SOFTENING OF PEROXIDE :—The active material on pasted positive plates softens, owing to the expansion and contraction on discharge and the action of escaping bubbles of oxygen formed on charge. This action loosens the particles on the surface of the plate and destroys the cohesion between the particles ; also they do not reduce back to PbO_2 (except partially), and therefore do not harden again. The acid mixes with these separated particles and produces the well-known soft, mushy substance, which, in course of time, is the condition of the entire mass, the effect described extending gradually through the whole thickness of the electrode.

No change in the chemical composition of the active material due to the softening process is discoverable.

Plates in this condition may be again brought to their healthy condition of hard PbO_2 by discharging, reversing and forming to sponge-lead, thereby causing a contraction of the active material and a firm cohesion of the various particles. Afterwards the electrodes are again reversed and changed back to PbO_2. The expansion of the particles fills up most of the pores, and as all the active mass is fully reduced to PbO_2, the plate regains its hardness. Some of the outer layer of active material will come off in the process, but usually the amount so lost is small, and if the reversal is carefully done, the results more than counterbalance the insignificant loss of peroxide.

(11) DRY PLATES.—If, for any reason, the negatives of a cell have been allowed to dry, a long time will be required for re-charging, the time required being almost the same as that for the initial charge. For this reason drying of the plates should be avoided as far as possible.

Positive plates, if dry, will require only a comparatively short charge ; if in a fully charged state when taken out of a cell, from 6 to 8 hours will be sufficient ; if discharged, then sometime longer. In any case, both the positive and negative plates of a cell must be fully charged before again being put into regular service. If new plates are installed, amount of charge noted above will likewise be required.

(12) SEDIMENT:—The accumulation of sediment in the bottom of the cells must be watched carefully, and removed, should it rise to within ½ inch below the bottom edges of the plates. Under no circumstances must the sediment be allowed to come in contact with the plates, as rapid deterioration would immediately result. It will be found that the depth of deposit is greatest under the middle plate, and *by levelling down the removal of the deposit can be postponed* for some time longer. This levelling must be done by using an L-shaped device, containing no metal in its construction. To remove the sediment, the simplest method, *if the battery have bolted connections between the cells*, is, after fully charging the battery, to lift the elements out of the jars, draw or pour off the electrolyte carefully, remove the sediment, clean the boxes with water, then replace the elements and cover quickly with electrolyte carefully, adding sufficient to compensate for that lost. *The negatives must not be exposed to the air except for the very shortest possible time, and must not be allowed to dry out in the least.* For this reason only one cell should be emptied, cleaned and refilled at a time. If *the cell connections are burnt together*, the deposit may be removed by using a special form of scoop for drawing it from beneath the plates and then removing it from the jar or tank. It will be necessary to temporarily draw up the wood separators, if the elements are thus equipped, while mainpulating the scoop. The separators should be handled very carefully to avoid breakage.

A third method is to draw off the electrolyte and flush the cell with water from the mains in such a way that the sediment will be continually stirred up, simultaneously drawing off the flushing water by means of a

syphon, continuing the operation until the cell is entirely free of sediment. The more rapid the flow in and out, the better. The water should then be withdrawn and the cell immediately re-filled with electrolyte. Do not allow the plates to dry out in the least. This method is usually only to be preferred when the cells are very large and where there is a strong head of water for stirring up the sediment.

A fourth method is to employ a pump or power syphon. A special pump for this purpose is supplied by the manufacturers.

In all cases where cells are cleaned out, it will be necessary to provide some new acid to compensate for wastage, and subsequent to the overcharge following the cleaning out, the gravity of each cell should be tested, and, if necessary, adjusted to 1·215° sp. gr. by the addition of 1·400 sp. gr. acid *The greatest care must be exercised, whichever* method be adopted, as otherwise the battery may be seriously damaged.

366. Battery of Individual Cells only used occasionally :—When a battery is not required for several weeks, it should be thoroughly charged and the plates well-covered with electrolyte. The cables should then be disconnected at the ends of each row to avoid any possibility of electrical leakage. Cells will remain in this condition for several months. If a charge can be given once every six or eight weeks, it is best to do so; this should be given at 75 per cent. of the normal rate and continued until the full charge is completed, and the plates gas freely. If a battery is to be used at infrequent intervals, it should be given an extended charge once every two weeks.

367. Calculation of Battery Output :—There are certain methods by which the amount taken out of a battery can be determined approximately without the aid of ampere-hour meters.

Of these methods the surest is by the fall in the specific gravity of the acid, because the fall or drop is almost directly proportional to the number of ampere-hours taken out. The total range in specific gravity over a complete discharge varies to some extent with the size

and design of the battery, and may be anywhere between 30 and 60 points. The operator should ascertain the exact value for his own battery. It should be noted that the range in specific gravity is almost the same irrespective of the initial specific gravity. For instance, if the specific gravity of the acid in the cell is 1·215° when fully charged, and for the particular battery the range over a complete discharge is 50 points, then at the end of discharge the specific gravity will be 1·215° minus 50°=1·165°; but if the specific gravity, when fully charged, is only 1·200°, the range would still be 50°, and the final specific gravity would be 1·200°−50°=1·150°.

Based on the above principle, the number of ampere-hours discharged from a battery can be determined approximately from the following rule:—

If X= specific gravity of the acid at the end of the last full charge, Y= the specific gravity to which the acid has fallen when making the determination, Z= the ampere-hour capacity of the battery stated on the instruction card, then the ampere-hours which have been taken from the battery $= \frac{X-Y}{60} Z$.

First subtract Y from X, which will give the number of degrees drop in specific gravity, then multiply the remainder by Z and divide the product by 60.

Example 11:—

A battery has a capacity of 300 ampere-hours. The specific gravity of its acid, which, when last fully charged, was 1 215°, has fallen to 1·185°. How many ampere-hours have been taken from it?

1,215−1,185=30. 30×300=9,000. 9,000/60=150.

The answer, therefore, is that 150 ampere-hours have been taken out of the battery.

In the above rule and example it has been assumed that the specific gravity falls 60 degrees or points during a complete discharge.

368. Taking a Battery out of Commission:— In any installation where the battery is to stand idle for

a prolonged period, unless arrangements can be made to give the battery a freshening charge once every three or four weeks preceded by a discharge, it is generally advisable to take it entirely out of service. When putting the battery out of commission, it is best to treat it and dry it off in the following manner :--

The cells should first be fully charged, that is to say, the charge should be continued until all the plates are gassing freely, and have a thoroughly healthy colour, and the acid has attained a maximum stationary specific gravity. The charge should then be suspended for an hour; should be resumed at half the normal rate until free gassing again takes place ; another hour's pause at half the normal rate should be given, re-charging should again commence at these intermittent charges and rests should be repeated until gassing takes place as soon as the charging current is switched on. (This process is useless if the plates are dipping in the deposit). All the cell connections should then be removed.

If the battery is a small one, the plates from the first cell should be lifted out ; the positive plates may be allowed to drain dry ; the negative plates should be plunged into a suitable vessel containing clean pure water. A spare glass box is the best, or the negative plates from the first two cells may be interlaced and placed in the first cell emptied, after the acid and sediment have been removed. The sediment in the cells should be saved as it has a market value.

369. Putting a Battery into Commission again:—When putting a battery into commission again, it should be treated exactly as a new battery. If the old electrolyte has been saved, a little extra acid will be required to compensate for wastage, to raise the level ½ in. above the tops of the plates. If new acid be used, the specific gravity should be 1·215°. When all the cells are filled, the charge should be started immediately, This charge is, in all respects, similar to the initial charge, and must be continued until the specific gravity and voltage have ceased rising for a period of ten hours. The average time required to complete this

charge is from 45 to 55 hours, employing the normal rate afterwards. At the completion of this charge the acid must be adjusted in each cell to the correct specific gravity (1·215 sp. gr.).

370. Applications of Storage Batteries :—

(1) Regulation of voltage on long feeders of trolley system.

(2) Propulsion--trucks, street cars, submarine boats, lunches, etc.

(3) Gas-engine ignition.
(4) Railway signalling.
(5) Telephone and telegraph.
(6) Portable and small stationary lamps.
(7) Fire and burglar-alarm system.
(8) Railway car lighting.
(9) Electrotyping.
(10) Dental and other surgical work.
(11) Source of constant potential and current in laboratory work,
(12) For changing volts by charging the cells in series and discharging them in parallel—or the reverse.
(13) For providing the different voltages for a multi-voltage system, as for a three-wire system or a five-wire system.
(14) For automobile starting and lighting.
(15) To reduce the amount of copper required for system supplying variable loads.

(16) To carry the peak load on a supply system.
(17) To insure continuous service.
(18) To carry the entire loads during periods of light demand.

(19) To regulate the loads on systems where the demand fluctuates widely. The battery enables the dynamos to work at constant full load on the station such as Buffer batteries in traction stations The steam consumption is thereby made uniform and considerable economy is effected.

Storage batteries are well adapted for certain classes of laboratory and testing work because the E. M. Fs., hence the currents, supplied by them, are perfectly steady—they are not subject to the variations that obtain when current is propelled by generators driven by engines or other prime movers. Furthermore, a variety of voltages may be obtained from one battery by using different series and multiple arrangements of the cells.

The Commercial use of the Storage Battery is limited because of :—

(*a*) Its high first cost and rapid depreciation.
(*b*) The additional mechanical complications introduced by reason of the regulating apparatus required. (*c*) The cost of maintenance.

371. Routine Works :—The amount of attention required by a battery varies with the working conditions, location, and, of course, the type of battery. The main points to be attended to are contained in the following condensed rules :—

A battery should be given just sufficient charging, neither too much nor too little.

A battery must not be run down too low on discharge.

A battery must not be allowed to stand completely discharged, nor must it be kept very long in a partially charged state.

Always keep the top of the plates covered with electrolyte by addition of water only.

Records should be regularly and accurately taken.

Inspect each cell of the battery carefully at regular intervals.

If any cell develops weakness, do not delay in bringing it back to a healthy condition.

Do not allow the sediment to reach the bottom edges of the plates before removing it.

Do not allow impurities of any description to get into or remain in the cells.

Keep all connections clean and tight.

Keep all iron, copper, or other metal work about the battery-room free from corrosion.

Keep the floor and other parts of the battery-room clean.

Keep the battery-room well ventilated, specially while charging.

Never bring an exposed flame into the battery-room during or shortly after the gassing period of a charge.

* **372. Daily Inspection** :—A daily inspection of the battery should be made systematically, and the following points should all be carefully noted :—

(1) The colour and feel of the plates.

(2) The colour of the deposit.

(3) That all the containers are sound (any irregularity in the level of the acid or any acid stains on the woodwork or floor are indications of a defective container).

(4) The level of the electrolyte.

(5) That no corrosion is present on the connectors or other metal parts of the battery or battery-room fittings.

(6) That the connections are clean and tight.

(7) The temperature of the battery-room and of the battery.

(8) The specific gravity of the acid in a representative cell called the " Pilot " cell, selected from the main part of the battery and not one of the end or regulating cells. The reading obtained should be recorded in a diary.

(9) The number of degrees drop in specific gravity of the acid, since the previous charge, and since the previous day should be calculated.

(10) The voltage of the battery should also be noted, but it cannot be too strongly emphasised that voltmeter readings taken without current passing have no value at all. In some instance it is found inconvenient to switch on load (lamps, radiators, etc.), but whenever possible the battery should be put on discharge for about ten minutes at the rate given on the card of instructions, by which time a true steady voltage reading may be obtained. An alternative is to book the voltage reading on ordinary load during the evening.

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(11) If ampere-hour meters are installed, the reading indicated on the dial of the discharge meter should be entered up on a log or record form. From the ampere-hour meter readings, and from the specific-gravity readings it can be decided if the battery should be charged on that particular day or if the charge may safely be left over until at least the following day.

(12) Do not let the DENSITY of the electrolyte in any cell differ from the standard density more than 0.005. Thus a cell having normal density of 1·200 should not register above 1·205 and below 1·195 when fully charged. Test each cell with hydrometer once a week at least.

(13) *Do not continue charge after* the negative plates begin to give off gas, except the occasional "boiling."

(14) *Never let charging current fall below* the 8-hr. rate except towards the end of charge, and

(15) *Stop discharge when* the battery potential falls to 1·75 volts per cell with the normal current; 1·70 volts per cell discharging at the 4-hr. or 1·60 volts per cell discharging at the 1-hr. rate.

(16) Give the battery a *prolonged overcharge about once a month.* This overcharge should continue at about 60 per cent. of the 8-hr. rate until free gassing of the negative plates has continued for 1-hr.

(17) Never let the *battery temperature* rise above 110 deg. fahr. and, if possible, keep below 100 deg. fahr.

(18) *Test each cell once a week with a cadmium electrode* and a low-reading voltmeter to determine the condition of the negative plates.

(19) Test the cells *occasionally for drop of discharge*; excessive drop indicates the presence of sulphate, and if the drop increases, the amount of sulphation is also increasing.

(20) *When one of a series of cells is sulphated,* charge it as usual in series with the others; on discharge cut the cell out, connecting the opened circuit by a heavy wire joining the two cells adjacent to the sulphated one. Be careful not to short-circuit the latter cell. When discharge is ended, remove connector and switch in the sulphated cell so that it again receives charge. Repeat

this process until the cell has had its sulphate fully reduced. A double-pole, double-throw switch is conveniently used to switch the cell and the connector alternately into and out of the circuit. With it the cell may be allowed to discharge a short time before cutting out, which improves the treatment.

(21) *Cells which stand a considerable time unused*—say as long as 45 days—should work in low density electrolyte not exceeding 1·21 specific gravity and be overcharged as directed in (20). It is better to give them a slight discharge and charge about once a week, if practicable.

(22) *Cells which are to be idle two months or more* should be taken out of commission by first fully charging and then discharging for two hours at the normal rate. Then draw off the electrolyte and fill the cells with pure water, preferably distilled. Begin discharge again at the normal rate. The cells will have to be practically short-circuited to produce this discharge in the water. When this discharge has been carried to a point at which the voltage is about 0·5 volt per cell, the water is poured out of the jars and the plates washed thoroughly by putting a hose in the jar and flowing the water over the plates. Allow the water which fills the jars at the end of the washing to remain 24 hours ; then pour it and allow the electrodes to dry. When the battery is to be used again, pour in electrolyte and give a prolonged overcharge.

373. I. Specification of a Lighting Plant for a Garden House :—Specify the generator and battery for a lighting plant with a connected load of 250 metal filament, 220-volt, 20-watt lamps, 16-candle-power each.

Watt per lamp=20.

Current per lamp=20/220=1/11 amp.

Current for 250 lamps = 250 × 1/11 = 23 amps., nearly.

Battery capacity at the normal 10-hour rate = 23 × 10=230 amp.-hours.

No. of cells in the battery=220/1·83=120 cells.

Say, type of cell, Chloride Battery S. L. G.4, 120 cells has got 240 ampere-hours capacity on 10 hours discharge and a normal charging rate of 32 amperes.

Maximum generator voltage $=120 \times 2{\cdot}7=324$ volts.

Minimum charging current at 8 hours rate = 29 amperes.

Generator output $=324 \times 29=9{,}396$ watts.

$=9{\cdot}5$ kW. nearly or the nearest standard size available in the market.

II. To find the size of the Engine see Chapter IV, p. 162.

III. Specify a booster set for the above:— Suppose that the supply is at 220 volts; find the size of the booster to charge the battery.

The minimum voltage of a cell is $1{\cdot}8$.

$\therefore$ minimum battery voltage $=1{\cdot}8 \times 120=216$ volts.

The maximum voltage taken per cell when fully charged equals to $2{\cdot}7$, the maximum voltage, therefore, equals to $2{\cdot}7 \times 120=324$ volts.

The booster will, therefore, have to give a voltage of 108.

The normal charging rate, if S. L. G. 4 battery is used, is 32 amperes.

The rating of the booster, therefore, may be taken as 32 amperes and 110 volts.

The booster will be a direct-current shunt-wound commutating pole machine separately excited from the 220-volt D.C. supply available. The rating of the booster will be 32 amps. 110 volts. The booster will be driven by a direct-current shunt-wound commutating pole motor operating on a 220/230 volt D.C. supply.

374. In Edison cells the positive plates consist of hollow perforated sheet steel tubes filled with alternate layers of flakes of nickel hydrate and metallic nickel. The hydrate is the active material. The negative plate is made up of perforated or flat sheet steel boxes or pockets loaded with iron oxide and a small amount of mercury oxide to provide conductivity. The

cell terminals and container are of steel and all metallic parts are mainly nickel-plated.

For action and further details of Edison storage battery *vide* p. 297, etc. Vol. I.

The electrolyte of Edison nickel iron storage cell is 21 per cent. of caustic potash containing a small amount of lithium hydrate.

The best charging of the Edison cells is at a steady rate equal to the normal discharge rate. During charging the current should be proportional to the number of plates and should not in an E P.S accumulator exceed ·026 amp. per sq. in.

The discharge voltage of an Edison cell is 1·2 volts.

The ordinary service portable Edison batteries have a watt-hour efficiency of 40 to 50 per cent. and portable lead batteries 65 to 75 per cent., the ampere-hour efficiency of the same batteries is 60 to 70 per cent for Edison and 80 to 90 per cent. for lead batteries. On very heavy loads, the watt-hour efficiency drops even lower than the lowest values given and on very slow discharge rate it rises higher than the highest values.

Space Occupied and Weight:—The net space occupied by an Edison battery is about 0·7 cu. ft. per kW. hour of energy to be stored.

That of a portable lead cell with pasted plates is from ·5 to ·7 cu. ft. and that of a lead cell with Plante plates about 1·5 cu. ft. per kW. hr.

The weight of Edison battery is about 75 lbs. per kW. hr; that of lead battery with pasted plates 65 to 125 lbs. and with Plante plates about 200 lbs. per kW. hr. The volume and weight of lead cells vary considerably depending on liberality of design, kW. hr. capacity, the kind of retainer, as well as on the kind of plates.

Alkaline batteries cost about 80 dollar per kW. hr. capacity. Portable lead batteries with pasted plates cost 30 to 55 dollar per kW. hr. capacity. The cost of stationary battery is 1·5 to 2 times that for pasted plates depending on size, liberality of construction and various other details.

375. Instructions for Periodical Overhauling of Nickel Iron Cells :—

1. The cells will be topped up to normal height.

2. The cells will be charged at normal rate until the voltage remains constant at 1·8 volts for 1½ hours.

3. The specific gravity of the electrolyte of each cell will be recorded.

4. Voltage of each cell will be taken on open circuit and recorded.

5. The cells will be discharged at normal rate until the voltage of the best cell drops to 1·1 volts.

6. The capacity of each cell will be calculated.

Edison cells, 300-amp.-hr. capacity, 60 amps. for 71 hours charging rate. For 450-amp.-hr. capacity, charging rate is 90 amps. for 71 hours.

7. If the capacity is low and the indication is that the loss of capacity is due to defective negatives, this can be improved by a cycle of charges and discharges at double the normal rate,

8. When the figures indicate that the trouble is due to the loss of capacity in the positive plates, the battery should be washed thoroughly and filled with new electrolyte of maximum of 1·190 at 60° F., and it should then receive a cycle of charge and discharge as in 7. The following table shows the maximum normal and minimum specific gravity permissible in various types of nickel iron cells. The specific gravities are for 60° F. and if the temperature is higher, the specific gravity can be worked out by decreasing the specific gravity by 5 points for every 20° F. increase in temperature.

		Nife.	Alconum.	Alkaline.
Maximum	...	1·210	1·200	1·200
Normal	...	1·190	1·190	1·190
Minimum	...	1·170	1·170	1·170

9. Electrolyte of a lower sp. gr. than 1·170 is never used in cells as it has a tendency to decrease the capacity of the battery. The normal useful life of electrolyte is from 18 months to 2 years.

The rates for charging various types of cells are as follows :—

	Nife.	Alconum.	Alkaline.
60-amp.-hr. ...	16 amps.	12 amps.	16 amps.
75-amp.-hr. ...	20 amps.	15 amps.	20 amps.
150-amp.-hr. ...	...	30 amps.	

The average life of nickel iron cells is about 10 years, and its capacity at the end of that period should be over 55 p. c. of its original capacity.

Capacities of Plante type stationary batteries at various rates of discharge.

Capacity in Ampere-hours
(expressed as a percentage of the ampere-hours available at the 5-hour rate)
When discharging in

1 Hr.	2 Hrs.	3 Hrs.	4 Hrs.	5 Hrs.	6 Hrs.	7 Hrs.	8 Hrs.	9 Hrs.	10 Hrs.
60 %	76 %	86 %	93·8 %	100 %	105·5 %	110·1 %	114 %	117·5 %	120 %

Capacity in Amperes
(expressed as a multiple of the amperes available at the 5-hour rate)
When discharging in

$\frac{1}{20}$ Min.	1 Min.	3 Mins.	5 Mins.	10 Mins.	15 Mins.	20 Mins.	30 Mins.	45 Mins.	60 Mins.
7·5	6·0	5·91	5·82	5·61	5·35	5·10	4·47	3·58	3·0

Miscellaneous Examples

Example 12. Two batteries are connected in parallel both being connected in series with a resistance of 100 ohms. One of the battery consists of 50 cells each of 2 volts and 4 ohms resistance, while the other battery consists of 100 cells each of 1·4 volts and 2 ohms resistance. What are the currents through each battery and the external circuit ?

(*a*) What must be the external resistance in order that no current should flow through the first battery ?

(*b*) That a current of ·05 amps shall flow through the first battery in opposite direction to that through the 2nd one.

(*c*) Explain why it is not possible by means of an external resistance alone to reduce the current through the 2nd battery to zero.

Solution :—

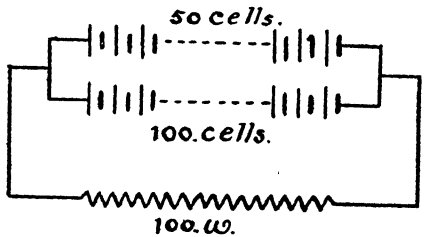


Fig. 6·12.

Let I_1 be the current in the 2nd battery

I_2 be the current in the 1st battery

and I the total current in the external circuit.

Now $I = I_1 + I_2$

The E. M. F. of the 2nd battery $= 1{\cdot}4 \times 100 = 140$ volts and, therefore, the terminal P. D. $= 140 - 2I$.

The E. M. F. of the 1st battery $= 2 \times 50 = 100$ volts and, therefore, the terminal P. D. $= 100 - 4\,I_2$.

Now, $140 - 2\,I_1 = 100 - 4\,I_2 = 100 - 4\,(I - I_1)$

or, $140 - 2\,I_1 = 100 - 4\,I + 4\,I_1$

or, $40 = 6\,I_1 - 4\,I$

or, $3\,I_1 - 2\,I = 20$ ... ... (1)

The drop in the external circuit$=R\ I=100\ I$, which is equal to the terminal voltage of the battery so—

$$100\ I=140-2\ I_1$$
$$or,\ 100\ I+2\ I_1=140 \quad \ldots \quad \ldots \quad (2)$$

From equations (1) and (2) we have—

$$I_1=7{\cdot}5 \text{ amps.}$$

From equation (1)—

$$2\ I=3\ I_1-20=22{\cdot}5-20$$

$\therefore\ I=1{\cdot}25$ amps.

and $I_2=I-I_1=1{\cdot}25-7{\cdot}5=-6{\cdot}25$ amps.

(*a*) When there will be no current in the 1st battery, the E. M. F. of the battery will be equal to the terminal P. D. of the battery.

Hence, $140-2\ I_1=100$

$\therefore I_1=I=20$ amps.

Again, $R\ I=100$ volts. $\therefore R=\dfrac{100}{20}=5$ ohms.

(*b*) The P. D. of the 1st battery$=100-(-4\times{\cdot}05)$ $=100{\cdot}2$ volts.

$$\therefore\ 140-2\ I_1=100{\cdot}2$$

$$\therefore\ I_1=\frac{39{\cdot}8}{2}=19{\cdot}9 \text{ amps.}$$

Hence, $I=I_1+I_2=19{\cdot}9-{\cdot}05=19{\cdot}85$.

Again, $RI=100{\cdot}2$

$$\therefore\ R=\frac{100{\cdot}2}{19{\cdot}85}=5{\cdot}035 \text{ ohms.}$$

(*c*) The E. M. F. of the 2nd batttery$=100$ volts and its P. D.$=140-2\ I_1$.

The E. M. F. of the 1st battery$=100$ volts and its P. D$=100-4\ I_2$.

If we reduce the current I_1 of the 2nd battery to zero, the terminal P. D. of the 2nd battery will be 140. Hence, the value for I_2 must be reduced so that its terminal P. D. may be 140 volts.

For reduced value of I_2 the value for the external resistance comes in reduced form, which is absurd.

Hence, we see by means of external resistance the current in the 2nd battery cannot be reduced to zero.

Example 13. Two storage batteries of E. M. F. 110 and 100 volts and internal resistances ·2 and ·25 ohms, respectively, are connected in parallel. They are then connected in series with a resistance of 5 ohms across 200 volts. Find the current taken by each of the batteries and from the main (City and Guilds Final, 1927).

Solution :—

Let I be the current taken from mains and I_1 and I_2 currents in the batteries reckoned positive when flowing in the direction of the arrows.

Then, we have $I = I_1 + I_2$ ... ... (i)

$200 = 5 \times I + 110 + \cdot 2 \times I_1$ ... (ii)

$200 = 5 \times I + 110 + \cdot 25 \times I_2$ ... (iii)

$\therefore \quad 110 + \cdot 2\ I_1 = 100 + \cdot 25\ I_2.$

$2\ I_1 = 2 \cdot 5\ I_2 - 100.$

$I_1 = 1 \cdot 25\ I_2 - 50.$

Substituting in (iii)—

$200 = 5\ (2 \cdot 25\ I_2 - 50) + 100 + \cdot 25\ I_2.$

$\therefore \quad I_2 = 30 \cdot 43$ amps. and is positive.

$I_1 = 1 \cdot 25\ I_2 - 50 = -11 \cdot 96$ amps.

I_1 is, therefore, negative; this battery is discharging at 11·96 amperes.

$I = 18 \cdot 47$ amperes current from mains.

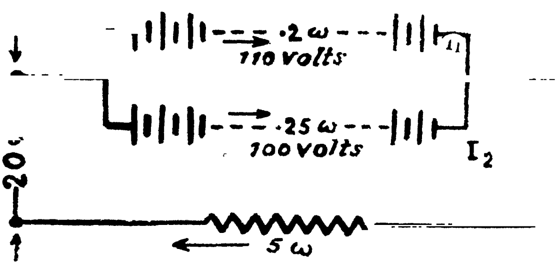


Fig. 6·13

Example 14. A 600-volt power station delivers energy to a transmission line of ·5 ohm resistance, at the end of which is a floating battery (E. M. F. $=540$ volts, Resistance 1·25 ohms). What is the maximum load that can be taken half-way between the station and the battery ?

Solution :—

Let W be the power taken.
V voltage at the centre.
I_2 current from the battery.
I_1 current from the station.

$$V=600-{\cdot}25\ I_1 \qquad \ldots \qquad \ldots \qquad (1)$$
$$V=540-1{\cdot}25\ I_2-{\cdot}25\ I_2 \qquad \ldots \qquad \ldots \qquad (2)$$
$$W=V\ (I_1+I_2) \qquad \ldots \qquad \ldots \qquad (3)$$

From (1) and (2)—

$$600-{\cdot}25\ I_1=540-1{\cdot}5\ I_2.$$
$$60+1{\cdot}5\ I_2={\cdot}25\ I_1.$$
$$I_1=240+6\ I_2.$$
$$V=540-1{\cdot}5\ I_2\ ;\ W=(540-1{\cdot}5\ I_2)\ (240+6I_2+I_2)$$
$$\frac{d\ W}{d\ I_2}=(540-1{\cdot}5\ I_2)\ 7-1\ 5\ (240+7\ I_2)-$$

This is zero for a maximum value of W, hence $21\ I_2=3{,}780-360=3{,}420$, $I_2=163$; $I_1=1{,}218$ and $V=2{,}96$

$$W=\frac{296\ (1{,}381)}{1{,}000}\text{kW.}=409\text{ kW.}$$

Provided the line and dynamo can stand such a load.

Exercises

(1) A battery has a discharging E. M. F. of 2·2 volts per cell at start and gradually falls to 1·8 volts at the end of discharge. If the internal resistance of each cell be 0·0004 of an ohm, what number of cells must be used (1) at the commencement, and (2) at the end of discharge, when they supply current of 60 amps. to a load the potential across which is maintained constant at 220 volts ?

(2) The E. M. F. of a certain accumulator was observed to be 2·2 volts on open circuit, but immediately fell to 1·95 volts when connected to an external circuit whose resistance was such that the cell discharged at 75 amps. What was the internal resistance of the cell ?

(3) A battery of 120 accumulators is charged with a constant current of 70 amperes for 6 hours, the average E. M. F. required to charge each cell being 2·3 volts. The battery is afterwards discharged at 80 amperes for 5 hours, the average discharge E. M. F. being 2·2 volts per cell. Determine (1) the quantity efficiency and (2) the energy efficiency.

(4) A battery consisting at 120 cells has to be charged with a current of 46 amperes from 230-volt supply mains. If the charging E. M. F. per cell at the commencement of charge be 2·1 volts, and 2·6 at the end of charge, determine the value of the resistance to be inserted in series between the battery and the supply mains (1) at the commencement of charge and (2) at the end of charge.

(5) How many cells would be required for a secondary battery of the ordinary lead type to supply 100 amperes for three hours to a 240-volt system ? If you were put in charge of such a battery and told to have it in readiness, how would you find out the state of the charge and how would you charge ?

(6) To what point should accumulators be discharged ? What is the suitable density of the acid that should be used in them ? How would you test a set of accumulators to discover whether they were fully charged ? What is the particular harm that results if accumulators are left long in a discharged state ?

(7) Describe, with sketches, one important type of lead storage cell suitable for heavy discharge work ; and explain the chemical changes taking place in such a cell during "charge," "discharge," and "rest." In what way, if any, are the E. M. F., life, internal resistance, capacity, and efficiency affected by the variations of the rate of charge and discharge, and by the specific gravity of the electrolyte ?

(8) Describe some form of secondary cell, and explain the electrical and chemical changes that will take place during charge and discharge. How does the ampere-hour capacity of a cell vary with the rate of discharge ? What precautions are necessary to keep a secondary cell in good working order ?

(9) Find the speed at start and end of charging for a dynamo to send 100 amperes through the battery of example one. The dynamo produces $\frac{1}{8}$th volt per revolution per minute, is separately excited, and has armature resistance 0·021 ohm. In charging each cell has B. E. M. F. ranging from 2·2 to 2·5 volts, and the battery is 40 yards away, and connected by lead of 0·003 ohm per yard.

(10) Find E. M. F. required to charge 60 cells in series, each having B. E M F. of 2·3 volts and 0·0005 ohm resistance. The dynamo resistance=0·03 ohm, add lead 0·04 ohm, and current 106 amperes.

(11) Give approximately the connection between the weight of a secondary battery, the horse-power which it can easily develop without injury, and the number of foot pounds which it can give out.

(12) If the E. M F. of a storage cell on charge and discharge be 2·2 and 1·95 volts, respectively, find the difference in the energy stored and restored in foot pounds when 100 ampere-hours are passed through the cell.

(13) A battery consists of 55 storage cells in series, each cell has a resistance of 0·001 ohm and E M. F. of 2·05 volts and consists of 10 positive and 11 negative plates $12'' \times 12''$. If 0·04 ampere per sq in. of positive plate surface be taken from the cell, what will be the P. D. at the distributing board at full load current, if the leads to the board have a resistance of 0·017 ohm.

(14) A storage cell contains 15 plates; each plate is $10''$ square and $\frac{1}{4}''$ from its neighbour. Find the resistance of the electrolyte if one inch cube of solution has 3 ohms resistance.

CHAPTER VII

ELECTRICAL MEASURING INSTRUMENTS

376. The most important properties or effects of an electric current utilised for its measurement are as follows :—

(1) The electromagnetic effect, from which magnetic field is created by the current, and lines of magnetic force are produced.
(2) The electrostatic effect.
(3) The heating effect
(4) The chemical effect.

All these effects are made use of, at the present day, in constructing electrical instruments to measure a current.

377. The Field of Measurement :—Two different kinds of currents have to be dealt with, namely, continuous and alternating, or periodic currents.

The first three effects are produced by both kinds of currents, the last effect is caused by continuous but not appreciably by alternating currents.

It is more difficult to accurately measure an alternating than to measure a continuous current and with some few exceptions, the same instrument will not measure both currents equally accurately. In some cases, an instrument for measuring an alternating current will not read accurately, when used on a circuit in which the rate of reversal, or periodicity of the alternating current is different.

378. The classification of electrical measuring instruments is five-fold—all instruments work on one or other of the five principles or effects, namely.

(1) Electromagnetic { (*a*) Moving needles
(*b*) Moving coil permanent magnet,

which makes use of the interaction between the magnetic field surrounding an electric conductor and the magnetic field around an iron core.

(2) Electrodynamic : which makes use of the force between two conductors, one moving and other stationary, carrying electric currents. The actuating forces are due to currents flowing through coils without iron cores.

(3) Electrostatic; which makes use of forces of attraction or repulsion between electric charges in two metallic plates and thus their action is independent of magnetic forces.

(4) Thermal : which makes use of the expansion of a wire by heat due to the flow of an electric current in the wire.

(5) Induction type instruments based on the principle of revolving magnetic field.

(6) Chemical.

The moving coil dynamometer and hot-wire types read equally accurately on either direct or alternating-current circuits, with the same scale, the other types having to be calibrated to suit the nature of the circuit in which they are used.

Instruments for measuring voltage or pressure may be divided into precisely the same forms as the ammeters, only the electrostatic type of voltmeter must be added.

The only difference between am- and volt-meters, with one or two exceptions, being in the gauge and in the number of turns with which the coils are wound.

The most important application of the wattmeter is in the measurement of electrical power in alternating-current circuits; it is difficult to get the true power in A. C. circuits otherwise.

The two kinds of electricity-supply meters are (1) those which integrate or sum up the products of the current and time throughout every instant of the day, and which are termed *coulomb* or *ampere-hour meters ;* (2) those which integrate or sum up the products of *the watts*

absorbed in any circuit and *the time* during every instant of the day, and which are called *energy* or *watt-hour meters*, though less often *energy* or *Joule-meters*.

379. Controlling Force :—All electrical indicating or measuring instruments have some moving part or system, which, when actuated by the current to be measured, are capable of taking up some temporary position of equilibrium between two positions of rest— one when no current flows, the other when the moving system will move no further, however large the current or deflecting force may be.

In all electrical measurements it is necessary to oppose and control the actuating force, so as to cause the deflection or speed of the moving parts, as the case may be, to vary to the actuating force; for otherwise, the moving part would deflect into the second position of rest at once, or race, as the case obtains and no useful result would follow.

The controlling forces are :—

(1) The resisting force or twist or pull of either a helical or spiral hair-spring.
(2) The torsion of some filament.
(3) The attraction of gravity.
(4) The attraction of permanent magnets.
(5) The attraction of an electromagnet.
(6) The electromagnetic action of current commonly termed magnetic or Foucault damping.
(7) The mechanical or air friction of a fan rotating with the system.

The spring is a common and important form of control, of which there are two varieties. The helical form of spring is used only on a few kinds of instruments and in one of the two ways possible, *e. g.*, to control by an axial extension.

The control by torsion or twisting up of one end of this form of spring is employed in the instruments known as "Siemens Electrodynamometer," "Torsional Moving-magnet voltmeter."

The force of torsion is directly $\propto$ to the angle of torsion.

First Form of Control :—The spiral hair-spring is largely used in instruments provided with a spring control. To work successfully, the turns should be uniformly spaced, and should not touch one another at any stage of their action.

The strength of either form of spring will be increased by decreasing the number of turns, or by increasing the section of the material with which they are wound and the material should be phosphor-bronze to avoid the bad effect of magnetism, *e g.*, sticking.

Second Form of Control :—The torsion of some filament is restricted almost entirely to laboratory or stationary instruments for testing purposes. An increase in the section or decrease in the length of the suspension will increase the tortional resistance of it. For a given suspension the torsion is $\propto$ to the angle of deflection.

Third Form of Control :—The attraction of gravity is very largely used, and, when it can be applied, is one of the most satisfactory methods. It is absolutely constant and is the cheapest form of control. "Gravity" instrument is usually cheaper to make than with any other method of control. The main disadvantage of the gravity type of instrument is that any change in the quantity being measured is not readable quickly enough, owing to the oscillatory nature of the motion of the parts, unless damped by a device working on the principle of number 6 or 7 above. Methods 2 and 3, perhaps, have the disadvantage that the instruments require to be very carefully levelled so that their pointers float exactly opposite zero. For stationary work this, however, is no disadvantage.

Fourth Form of Control :—It is not much used. Its disadvantage is that in the presence of powerful external magnetic fields the magnetism is liable to be temporarily, or even permanently, affected and changed, thus either temporarily or permanently altering the sensibility and calibration of the instrument.

The three remaining methods of control apply only to rotatory measuring instruments, *i.e.*, to the motor class of electricity meters.

380. Sources of Error :—(1) Error in the calibration, owing to the standards employed in the two cases being different.

This applies to all instruments, and cannot well be remedied except by recalibration.

(2) The errors due to friction at the pivots in all types of instruments which contain pivoted parts.

These can be minimised, though not eliminated, by making the weight of such parts as small as possible.

(3) Errors due to *changes of temperature* in all types of instruments containing high-resistance shunt coils, *i.e.*, coils passing potential currents, such as that of the electro-magnetic voltmeter, the fine wire coils of wattmeters and electricity meters, etc.

(4) Hysteresis error in instruments containing very soft iron and low magnetic induction.

(5) Gradual alteration of sensitiveness due to the weakening of (*i*) permanent magnets or (*ii*) of spring.

(6) Effect of external magnetic field.

(7) Defective levelling—specially instruments in which moving parts are suspended.

(8) Variation of sensitiveness caused by alteration in frequency or wave form in the case of alternating-current instruments.

(9) Self-induction-A. C. instruments read lower than D. C. instruments. This is specially serious in wattmeters.

381. Method of Diminishing the Heating Error to a Minimum :—Wind the working coil of the instrument with copper wire so as to obtain a large magnetomotive force and deflection with the least energy wasted. Connect in series with this working coil, another coil, wound non-inductively with such a material as manganin, so as to have a large radiating surface.

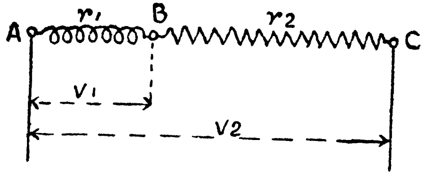


Fig. 7·01

If, then, V_1 volts produce a deflection θ, when applied directly to the working coil AB, and

V_2 volts the same deflection θ, when applied to the combination AC, of which A and C are now the terminals, and if r_1, r_2=resistances, respectively, of working and of extra coil ; then $V_1/V_2 = r_1/(r_1+r_2)$.

Under these circumstances, though r_1 may vary considerably, it is so small a fraction of r_2 that r_1+r_2 practically remains constant at all temperatures.

A further advantage is that this principle enables high voltages to be measured when only a low-voltage instrument is available.

382. Compensating Devices:—The moving-needle electro-magnetic instruments require a compensating device to measure accurately, with the same scale graduations, direct or alternating currents, and P. D.s of any periodicity.

One method of compensation employed in ammeters and voltmeters is to shunt the working coil with an inductive choking coil, which, with continuous currents, shunts off some 5 o/o of the current from the working coil. When the instrument is used for alternating currents, the choking coil, by reason of its inductance, creates a back E. M. F. in its own circuit, thus allowing only some 2 o/o of the current to be shunted, leaving the additional 3 o/o for the working coil, which is sufficient to raise the readings to the correct effective value.

383. Characteristics of Different Types of Instruments :—

I. Moving-Needle Electro-Magnetic Instruments :—(*a*) This type comprises all instruments in which a piece of soft iron, free to move, is sucked or attracted from a weaker to a stronger part of the field due to a main solenoid, suitably wound.

(*b*) The controlling force used may be either gravity or that due to a spring, or in one or two instances that of a permanent steel magnet.

(*c*) *Sources of Error* :—

(1) The alteration in the strength of the permanent magnet in cases where this is used as the control.

(2) The sensibility of the instrument being temporarily altered by external magnetic influence; this is minimised by the magnetic screening.

(3) The alternation of periodicity in alternating-current instruments—inductance and eddy currents error.

(4) The change of temperature due to (*i*) internal ohmic loss, (*ii*) chamber error, in the case of voltmeters.

(*a*) by causing expansion of parts.

(*b*) by altering the permeability of iron.

(*c*) by altering the resistance of the coil.

The method of minimising this is mentioned before.

(5) Wave form error.—The same current giving different deflections, depending on whether it is rising or falling.

(6) Hysteresis and position error—manifested in two ways (*a*) in the lagging of the magnetism behind the current, (*b*) movement of the position of the poles in the iron with the rotation of the system known as position error.

(7) Friction error.

(d) *Advantages and Disadvantages of Moving Iron Type :—*

(1) Simplicity of construction.

(2) Cost—low (least expensive of all types).

(3) Adaptability—suitable for both D. C. and A. C.

(4) Accuracy—least accurate excepting Thomson-ammeters which are quite accurate for alternating-current measurements and mostly used for switchboard work.

Action :—

(*a*) In a continuous-current system, Pull$=I \times \phi$, where I is the current and ϕ is the corresponding magnetic flux in the plunger.

If the iron is not oversaturated—

$\phi = KI$, where K is a constant.

Pull $= KI^2$.

Or, pull is proportional to the square of the current.

(*b*) In an alternating-current system, if i and m are the instantaneous values of the current and the flux, the instantaneous pull$=Ki^2$.

The direction of the pull is the same, as both the directions of the current and flux change their sign simultaneously. Further, the inertia of the moving mass prevents it from following the fluctuation in the value of the pull, the needle assumes the position corresponding to the average pull.

$$\text{Average pull} = K.\ \frac{1}{T}\int_{0}^{T} i^2 dt = KI^2$$

where T is the duration of one cycle of the alternating current

A calibration made with direct current is true within a few per cent. with alternating currents. The difference is due to the effects of (1) saturation in iron for which ϕ varies, (2) hysteresis, (3) eddy currents.

(*i*) Ascending readings differ from descending readings due to the hysteresis of soft iron.
(*ii*) Readings affected by strong fields.
(*iii*) Cramped scale at the lower and also the upper end, if the scale is continued so far.

(*iv*) Operation—usually not dead-beat in their action.

II. The Moving-Coil Permanent-Magnet Type:— It has a spring control while a larger deflecting torque is obtained with this than with any other form of electromagnetic instrument.

Advantages and disadvantages of moving-coil permanent-magnet type :—

(1) *Adaptability* :—Not suitable for A. C. circuits, since the direction of deflection depends on the direction of the current. For accurate direct-current measurements this type is used exclusively.

(2) *Accuracy*—can be made very high.

(*i*) Ascending and descending readings the same.
(*ii*) Not affected by stray fields.
(*iii*) The error due to the increase of resistance o the coil with temperature is usually reduc e to a minimum by the use of a resistance of

alloy having a zero temperature coefficient, connected in series with the moving coil.

(*iv*) An error may be gradually introduced by the weakening of the permanent magnet, but this is guarded against by using a magnet built up of a number of hard steel magnets and by careful aging.

(*v*) Operation—dead-beat.

(*vi*) Having uniformly divided scale from end to end.

III. Electro-dynamic Instruments:—The force between two conductors carrying electric currents is called electro-dynamic attraction or repulsion. In electro-dynamic instruments the actuating forces are due to currents flowing through coils without iron core.

The Moving-coil Dynamometer:—(1) It contains no iron in the working parts, it is independent of variation, of periodicity, and in most cases of "wave form" of the circuit. It is equally accurate on either direct or alternating-current circuits; but is subject to error (*ii*) above, in addition to those enumerated before.

(2) The control employed is necessarily that of two springs, set so that one uncoils as the other coils, thereby avoiding alteration of zero through change of temperature affecting the springs.

The main advantage is that this type contains neither iron nor permanent magnets in its working parts.

Note that Kelvin balance operates upon the electro-dynamometer principle, but it is usually classed separately because (1) the controlling force is gravity, (2) the planes of the coils are horizontal instead of vertical and the movable coils do not rotate about a central axis, but revolve about an axis midway between them.

Advantages of Electro-dynamic Type:—Sensitiveness, accuracy and adaptability to both direct and alternating current measurements. It may be calibrated on direct current and used on alternating current.

Disadvantage:—Siemen's dynamometer and Kelvin's balance are not direct-reading; they are not dead-beat and

hence require considerable time and skill in taking readings. The necessity for accurate levelling is also a disadvantage.

(1) *Adaptability* :—Suitable for both D. C. and A. C. circuits.

For accurate alternating-current work, dynamometer type and hot-wire instruments are used to a considerable extent.

(2) *Accuracy* :—Fairly high.

(*i*) Scale contracted at the beginning.

(*ii*) Affected by stray fields.

(*iii*) Temporary error minimised as in moving-coil type.

(*iv*) Frequency error when used on A. C. circuits minimised by making the inductance of the coils very small in comparison with their resistance.

(3) *Operation* :—A dead-beat action is secured, usually by means of a light aluminium piston attached to the right arm of the lower end of the pointer, and moving in an air chamber.

The torque between the two coils is proportional to the currents i_1 and i_2 between them.

$\therefore$ torque $=K_1\, i_1\, i_2$.

The coils being in series $i_1=i_2=i$.

$\therefore$ torque $=K_1\, i^2$.

The torque is balanced by the torsion of the spring and the spring is wound so that the twisting force is proportional to the angle of torsion or torque $=K_2\, \theta$.

$\therefore K_1\, i^2=K_2\, \theta$.

or, $i=\sqrt{K_2\, \theta/K_1}=K\sqrt{\theta}$.

With alternating current the expression becomes

$$\text{torque}=K_1 \frac{1}{T}\int_0^T i^2\, dt=K_1\, I^2.$$

Example 1. A centimeter balance was used to calibrate a millivoltmeter. The millivoltmeter reading was 672 milliamperes, and the balance reading was 324 on the lower scale. How much is the ammeter in error if the constant for the weight used is two ?

Solution :—

$2\sqrt{324}=36.$

$I=2\times36=72$ centiamps. = 720 milliamps.

Error$=720-672=48$ milliamps.

IV. The Induction Type :—Controlling force—Light spiral spring or gravity—No electrical connection is needed to the moving parts, and these moving parts are of the simplest description.

Advantages and Disadvantages of the Induction Type.

(1) *Adaptability* :—Suitable for A. C. circuits only.

(2) *Accuracy* :—Scale is open and extremely long and the readings are usually accurate, provided the frequency of the circuit on which they are used is constant at the value for which the instrument has been calibrated. Since the deflecting couple is dependent on the frequency of the current passing through the instrument, this type is unsuitable for measuring on varying frequency.

Portable induction type instruments are very convenient and are sufficiently accurate for many practical purposes.

The chief disadvantage is that it cannot be calibrated with continuous current.

The coil of one electro-magnet carries the main current or a definite part of it and thus produces a magnetic flux very nearly in phase with the main current. The coil of the other electro-magnet with an *induction* resistance in series with it is connected across the mains. It thus carries a current proportional to the P. D. but it lags by nearly 90° producing a corresponding flux. The torque exerted on the disc varies as the product of the two fluxes and as the sine of their phase difference.

Hence, the torque is approximately proportional to $E\,I\,Sin\,(90-\phi)=E\,I\,Cos\,\phi$. It is liable to errors due to inductance, resistance and capacity.

V. Hot-Wire Instrument :—(1) Expansion instruments, (2) thermo-junction instruments. The heating effect of the current is made use of for indicating the current or pressure to be measured.

Advantages and Disadvantages of Hot-Wire Type

Disadvantages :—They absorb a good deal of energy, and will not indicate voltages lower than about one-fifth of the maximum. Uncertainty of zero (on the scale) as the scale is crowded in the lower portions.

(1) *Adaptability* :—Hot-wire instruments will measure accurately, direct, as well as alternating, currents of any "wave form" or "frequency" which must not be so high as to increase the effective resistance of the wire

They are absolutely free from temperature errors, as the heating effect is made use of in the actual measurement. But when left long in the circuit there are errors due to change of surrounding temperature and heating. They are dead-beat, direct-reading, and absolutely unaffected by external magnetic fields.

(2) *Accuracy* :—Moderately high.

(*i*) Subject to zero creep due to change in physical condition.

(*ii*) Not affected by stary fields.

(3) *Operation* :—

(*i*) Take some time to give reading,

(*ii*) Difficult to repair.

(*iii*) Must be calibrated throughout their range with the shunt with which they are to be used (ammeter only).

(4) They cannot stand much overload without burning out.

If r be the resistance of the 'hot-wire,' the average heat generated in it with alternating current is—

$$\frac{1}{T}\int_0^T (i^2 r)\,dt = r.\frac{1}{T}\int_0^T i^2\,dt = r\,I^2 \text{ effect.}$$

Hence, a hot-wire instrument calibrated with direct current shows true effective value of alternating current.

Voltmeters of over 10 volts can be protected by fuses renewable from the outside, but for lower pressures such protection is impracticable on account of high resistance. Ammeters can be protected from injury in a simple way by an automatic short-circuiting switch.

The Error due to Change of Temperature :—In all types of instruments having a high-resistance coil carrying potential currents, there is an error due to change of temperature.

Let I=current passing through the coil of a voltmeter.

R=resistance of the coil.

E=the potential across the voltmeter.

Now, $E=IR$.

If E remains constant and R varies, I will also vary and the reading will thus vary.

Example 2. The resistance of the working coil of a moving iron voltmeter is 6,600 ohms at 20°C., at which temperature it was calibrated and read correctly when connected across a potential of 220 volts. The coil is wound with copper wire having a temperature coefficient of 0·0043. Calculate the percentage error in the reading when the temperature of the working coil increases to 50°C.

Solution :—

The current flowing in the coil at 20°C.

$= E/R_{20} = 220/6{,}600 = 0{\cdot}033$ amp.

Which gives a full-scale deflection corresponding to 220 volts. The current flowing in the coil at 50° C.

$= E/R_{50} = E/R_{20}\ (1+\alpha t)$

$= 220/6{,}600\ (1+0{\cdot}0043\times 30) = 0{\cdot}295$ amp.

Thus, the current energising the solenoid is reduced, so also will be the voltmeter reading. With ·033 amp. through the coil the needle indicated 220 volts ; hence if the iron be saturated, ·0295 ampere will indicate

$220 \times {\cdot}0295/{\cdot}033 = 197$ volts.

So, the error introduced due to change of temperature $= -23 \times 100/220 = -\ 10{\cdot}5$ per cent. That is, the voltmeter indicates 10·5 per cent. low.

Example 3. An alternating sine wave P. D. with a maximum value of 100 volts is applied to a non-inductive resistance of 5 ohms. A hot-wire ammeter and a moving coil ammeter are connected in series in the circuit. Find the reading on each.

Solution :—

Hot-wire ammeter reading$=100/5\sqrt{2}=14·15$ amps. In moving coil ammeter, since the direction of deflection depends on the direction of the current, the reading is zero.

Example 4. A rectified sine wave P. D. having a maximum value of 100 volts is applied to a non-inductive resistance of 10 ohms, what will be the readings on a moving coil and a hot-wire ammeter respectively connected in series with the resistance ?

Solution :—

In the moving coil $I=2\ I\ \text{max.}/\pi = 6·36$ amps.

In the hot-wire $I=\dfrac{I\ \text{max.}}{\sqrt{2}} = 7·07$ amps.

Example 5. A direct-current change in strength every second from 10 to 5 or from 5 to 10. Find the steady current which has (*a*) the same electrolytic effect, (*b*) the same heating effect.

Solution :—

(*a*) Average value$=(10+5)/2=7·5$ amps.

(*b*) Effective value=

$$=\left(\frac{10^2+5^2}{2}\right)^{\frac{1}{2}}=7·9 \text{ amps.}$$

VI. Electro-static Instruments :—These are employed for measuring E. M. F.s and depend for their action on the electro-static attraction and repulsion between fixed and movable conductors close to, but insulated from one another. Their action is independent of magnetic forces.

The control is usually gravity, but sometimes torsion of a wire or spring is employed.

Advantages and Disadvantages :—This type of instrument possesses the great advantage of being non-magnetic, and, therefore, entirely unaffected by external magnetic fields. They do not consume any electric current in D. C. and very little in A. C. circuits. They are entirely unaffected by temperature, external magnetic

fields, power factor or frequency and wave form and may be used on very high potential circuits. These are used mostly in high-tension work and in special research.

The *disadvantage* lies in the fact that low voltages are not easily or clearly indicated, and that the scales of such instruments are usually somewhat short and the divisions a little crowded in consequence. It has small ratio for torque to weight of moving parts causing errors due to friction.

(1) *Adaptability* :—It is equally accurate on direct and on alternating current circuits of any periodicity or wave form, as it has no self-induction, but, on the contrary, an extremely small capacity. It has no temperature error, and consumes no energy at all, as the terminal resistance is practically infinitely large.

(2) *Accuracy* :—Very high and accurate reading can be obtained even with low power factors.

(3) *Cost* :—Very high.

(4) They are specially suited to high pressure, because they do not possess any high non-inductive resistances.

(5) There is not much danger of over-loading the instruments as with ordinary wattmeters.

In electro-static voltmeter, if the vane remained stationary, the force of attraction would be proportional to the square of the potential difference between quadrants and vanes.

$$F=KE^2.$$

The accuracy is impaired when the capacity is slightly changed with the change in their position.

384. The principal requirements for good measuring instruments are :—

(1) The calibrations must be permanent.

(2) Stray magnetic fields must not be capable of affecting the instrument readings.

(3) "Dead-beat" quality, *i.e.*, the instrument should not swing too long before giving definite indication.

(4) The scale must be of a suitable character.

In modern ammeters and voltmeters all these requirements are met to larger or smaller degree. The more strict the requirements, the more expensive becomes the instrument. Do not demand greater accuracy than a specific case may require.

(1) The calibration may be affected by a change of form or relative position of parts inside the instrument; by an increased friction in pivots; by aging of springs or of iron; by permanent magnet losing part of their magnetism.

(2) The effect of stray fields can be sufficiently avoided by being inclosed in a cast-iron case. Induction instruments are affected very little, since their air-gap is small and their own field quite strong. Hot-wire instruments, as they do not depend on magnetic effect, are practically unaffected by stray field. Electro-magnetic instruments are affected the most, and *should never be placed near* dynamos, or on a switchboard within a loop of busbars and cables carrying strong currents. Electro-dynamometer type instruments are affected by terrestrial magnetism when used on direct current, therefore, in accurate measurements, it is essential to reverse the current in the instrument and to take the average of two readings.

(3) The "dead-beat" or periodic quality is always desirable in an instrument. It is usually attained only by the addition of an extra damping device such as the use of an aluminium vane. The *damping* is attained either by the resistance of the air to the movement of the vane, or by placing the vane between the poles of a permanent magnet, so as to induce in it eddy currents. Moving-coil instruments are easily made "dead-beat" by making the frame of the moving coil of aluminium. Eddy currents induced in it by the permanent magnet are sufficient to make the instrument dead-beat.

(4) A somewhat different character of scale is provided in different types of instruments. The scale of moving coil instruments is usually perfectly regular, all divisions from zero to full scale being equal. Hot-wire instruments have rather an irregular scale divisions which

are crowded on the lower part of the scale, so that the instrument can be read with fair accuracy at not less than 40 per cent. of its full range. Sometimes the scale is made suppressed on purpose, in its lower part, so as to have larger divisions in the useful range of the instrument. In instruments based on the hot-wire or dynamometer principle, the scale is irregular, since the deflecting force is proportional to the square of the current. A regular scale is not always desirable in switchboard service, though it is very convenient in testing and for experimental purposes, since it increases the useful range of the instrument.

It is of vital importance that (1) the resistance of voltmeters should be invariable, so that the current flowing through them will always be proportional to the E. M F. at their terminals.

(5) That the resistance of voltmeters should be high.

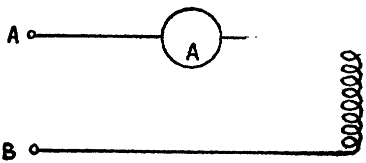
385. Cell-Testing Voltmeter :—A good cell testing voltmeter must be "dead-beat," spring-controlled, of the permanent magnet type, dust and acid proof, of high resistance and weight, and it should read to 3 volts on either side of central zero, and should be fitted with a device to set the needle absolutely on zero.

386. Use of Ammeter as Voltmeter :—An ammeter in series with a known high resistance can be used as a voltmeter, for the difference of pressure is equal to the product of the current and resistance. The set, however, must be connected to the two points *A*, *B*, the P. D. between which is to be determined (Fig. 7·03).

An ammeter with extreme range of 0·1 amp. and a resistance of 1·0 ohm is connected in parallel with it a shunt of more than 0·001 ohm, the current will now be divided into 2 parts, 999 parts passing through the shunts and one part through the instruments. The instrument is now capable of measuring 100 amps. The same instruments may be used as a voltmeter. To do this we actually measure the current through a known resistance and calculate the corresponding voltage. By choosing a suitable value for the resistance the calculation becomes very simple or by using a suitable scale the

reading may be made direct. Thus, if the instrument be considered connected in series with 999 ohms, the total resistance of the circuit will be 1,000 ohms. If we should apply 100 volts to the circuit a current of 0·1 amp. would flow; this, we have assumed, will give the full scale deflection of the instrument. If we mark the point to which this current deflects the pointer 100, it is evident the reading will be direct. Similarly, if 99 ohms be connected in series with the instrument, its maximum reading will be 10 volts, while 4,999 ohms would give it a range of 500 volts. Thus, one instrument provided with suitable shunt and resisters may be used to measure a very wide range of currents and voltages.

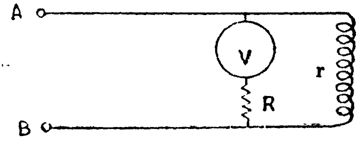
All voltmeters act on this principle, with the exception of electro-static ones, which are used mainly for alternate current. The reading is not taken in amperes and then multiplied by the resistance, but the scale is marked so as to read volts directly.



Ammeter Connection

Fig. 7·02.

For similar instruments the resistance is usually increased in proportion to the maximum voltage, consequently the power wasted increases in the same proportion.



Voltmeter Connection.

Fig. 7·03.

Example 6. A milliammeter reading up to 500 milliamperes has a resistance of 0·1 ohm. How could this instrument be used or adopted to read (*a*) voltages up to 220 and (*b*) current up to 25 amperes.

Solution.—

(*a*) $E=IR=500\times 0{\cdot}1=50$ millivolts; $\therefore$ resistance in series must be $(220-0{\cdot}05)\,0{\cdot}5=439{\cdot}9$ ohms.

(*b*) Shunt in parallel required is equal to voltage drop divided by current flow through the shunt

$$=0{\cdot}05/19{\cdot}5=0{\cdot}0025 \text{ ohm.}$$

387. To Determine the Size of Wire Required for a Voltmeter Coil:—The ampere-turns TI required to deflect the needle of a particular instrument over the scale can be determined experimentally, and the voltage E impressed on the working coil is a known factor

Let I = current flowing through the coil.
R = resistance of the coil.
l_m = length of a mean turn on the coil.
l = total length of wire forming the coil.
a = area of cross-section of wire.
d = diameter of wire.
ρ = specific resistance of wire.
T = turns constituting the coil.

Then $E/I = R = \rho \times l/a$

but $l = l_m \times T$ and $a = \pi d^2/4$

Therefore, $E/I = \rho \times l_m \times T \times 4/\pi d^2$

or, $d^2 = \rho \times l_m \times 4 \times TI/\pi E$

From the above the diameter of the wire is given by

$$d = \sqrt{4 \times \rho \times l_m \times TI/\pi E}$$

Example 7. The working coil of a moving soft-iron voltmeter reading up to 220 volts requires 660 ampere-turns to give a full scale deflection. Find the diameter of wire for the coil if the wire be of copper having a specific resistance of $1{\cdot}6 \times 10^{-6}$ ohms per centimeter cube ; the mean length of one turn = 15 centimeters.

Solution:—

Substituting in the formula :

$$d = \sqrt{\frac{4 \times \rho \times l_m \times TI}{\pi E}}$$

$\rho = 1{\cdot}6 \times 10^{-6}$ ohms per (cm.)^3, l_m = 15 cms.,
$TI = 660$, $E = 220$ volts

We have, the diameter of the wire

$$d = \sqrt{\frac{4 \times 1{\cdot}6 \times 10^{-6} \times 15 \times 660}{\pi \times 220}} = 0{\cdot}095 \text{ mm.}$$

The moving soft iron must be saturated in order to obtain a uniform scale with these instruments.

The deflection is due to the reaction between the two magnetic fields, one due to the moving soft-iron which is turned a temporary magnet owing to the electro-magnetic action of the current and the other is due to field of the other magnet. If the moving iron is saturated, its strength remains constant so that the deflection is proportional to the strength of the other field produced by the current flowing in the coil.

The variation of B with H is irregular below the saturation point. Hence, the scale of an instrument in which the iron is not saturated. cannot be evenly divided. Consequently, moving soft-iron instruments for measuring currents or voltages are not calibrated when below the saturation point, or the lower part of the scale of these instruments is very often left blank.

388. Best Size of Wire in Permanent Magnet Instruments :—

Let v = volts across coil.

l = mean length of one turn.

b = the breadth of former.

n = number of turns.

i = current through windings.

R = resistance of windings.

R_1 = resistance of leads and springs.

a = radius of wire.

I = moment of inertia of coil.

G = galvanometer constant.

We see that

Resistance $= \rho l n/\pi a^2$, Current $= v\ \pi a^2/\rho l n$,

Ampere turns $= v\pi a^2/\rho l$.

In an ammeter we require maximum ampere-turns for a given voltage drop. This is obtained by making a as large as possible.

The limits are : (a) The air-gap must be kept small; (b) springs have an appreciable resistance.

Hence, the expression for current becomes

$$\frac{v}{\rho ln/\pi a^2 + R_1},$$

and ampere turns $= \dfrac{v\,n}{\rho ln/\pi a^2 + R_1}.$

In order that this quantity be a maximum for a given value of v, its reciprocal must be a minimum.

Let $\quad y = \rho ln/\pi a^2 vn + R^1/vn,$

$$= \rho l/\pi a^2 v + R_1/vn.$$

In this a and n are variables, n being a function of a.

Approximately, $n = b/$diameter of insulated wire, or

$$n = kb/2a.$$

The quantity k corresponds to the usual space factor.

Hence, $\quad y = \rho/\pi a^2 v + R_1\, 2a/vbk.$

Differentiating and equating to zero, we find finally that

$$R = R_1/2,$$

or if the resistance of the coil be one-half that of the external resistance, the ampere-turns are a maximum for a given volt drop. If a series resistance of low temperature coefficient be employed, R_1 = resistance of springs + leads + the external resistance.

Now with regard to the voltmeter.

Here the v becomes E the voltage, and the usual expression for size of wire is

$$a = \sqrt{\frac{\text{ampere turns} \times \rho l}{\pi E}}.$$

This expression gives much too fine a wire for practical purposes and consequently to reduce this and diminish temperature errors a series coil is used.

389. Best Shape of Coil :—Assume flux density, number of turns and area of coil constant. Hence, area $= \rho l$ for a rectangular section of the coil. The minimum resistance is given by minimum perimeter, *i.e.*, a square.

Example 8. The control of a particular moving-coil instrument is such that it requires a force of 1 gramme-centimeter to produce a full scale deflection,

is ·01 of an ampere. From the following data calculate the number of turns required for the moving coil:—

Diameter of moving coil $(d)=2$ centimetres.

Length of active conductor $(l)=3$ centimetres.

Flux density in air-gap $(B_a)=1{,}000$ lines per square centimetre.

Solution:—

The force acting on one conductor$=B_a \times l \times 0{\cdot}001$ dynes

If n denote the number of turns required for the moving coil, then the force acting on one side of the coil

$$=B_a \times l \times n \times 0{\cdot}001 \text{ dynes},$$

$$=\frac{B_a \times l \times n \times 0{\cdot}001}{981} \text{ grammes.}$$

The total moment, producing rotation, is given by

$$\frac{B_a \times l \times n \times {\cdot}001}{981} \times d = 1 \text{ gramme-centimetre,}$$

$$\text{so that } n = \frac{1 \times 981}{0{\cdot}001 \times B_a \times l \times d} = \frac{1 \times 981}{0{\cdot}001 \times 1{,}000 \times 3 \times 2}$$

$$=163{\cdot}5, \text{ or, say, } 164.$$

∴ Turns required for moving coil = 164.

Example 9. In a moving-coil voltmeter reading up to 500 volts a current of 0·05 of an ampere is required to produce a full scale deflection. If the error due to temperature-change must not exceed 0·05 per cent. of the maximum reading, with a rise in temperature of 25° C, and the moving coil is wound with copper wire having a temperature coefficient of 0·43 per cent. per degree centigrade, calculate the value of the manganin resistance in series with the moving coil, manganin having a zero temperature coefficient.

Solution:—

Total resistance of voltmeter circuit at ordinary temperature

$$=E/I=500/{\cdot}05 = 10{,}000 \text{ ohms.}$$

When the temperature increases by 25°C., the current in the moving coil is reduced by 0·05 per cent. and

$=(99·95/100)\times·05=·049975$ amp.

Therefore, the resistance of the voltmeter, when the temperature rises 25°C. above normal, must not exceed 500/·049975 = 10,005 ohms.

∴ increase in resistance = 10,005—10,000 = 5 ohms.

The copper increases $0·43\times25=10·75$ per cent. per 25°C. So that the normal resistance of moving coil

$=100\times5/10·75=46·5$ ohms.

The manganin resistance must, therefore, have a value of 10,000 — 46·5 = 9,953·5 ohms.

The resistance of the moving coil is quite low compared with that of the manganin resistance.

Example 10. In a certain moving-coil instrument, 0·05 of a volt is sufficient to produce a full scale deflection. It is proposed to use the instrument to indicate a maximum current of 250 amperes. If the shunt be made from manganin strip 0·6 millimeter thick, calculate the dimensions of the shunt. Specific resistance of manganin = 43 microhms per centimeter cube.

Solution :—

The instrument requires 0·05 of a volt for a full scale deflection. Hence, the voltage drop in the shunt must equal this value when the maximum current, the instrument has to indicate, passes through the shunt. Thus, the resistance of the shunt is given by

$R_s=E_s/I_s=·05/250=0·0002$ ohm.

Shunts are generally designed for a temperature rise of about 30°C. When carrying continuously their full load, and in order that the temperature increase may not exceed, the shunt must have a radiating surface of 12 square centimetres per watt absorbed.

In this case the watts absorbed

$=E_s\times I_s=·05\times250=12·5$ watts.

Therefore, the total radiating surface must be

$=12\times12·5=150$ sq. cms.

But there are two sides of the strip exposed to the atmosphere, so that the surface per side = 150/2 = 75 sq. cms. Let l = length of strip, b = breadth, and t = thickness ; then, $l\times b=75$ sq. cms.

Now, the resistance of the shunt is also given by the equation—

$$R=\rho\times l/a,$$

where a =area of cross-section of the strip.

Thus, $\cdot0002=43\times10^{-6}\times l/a=43\times10^{-6}\times l/b\times t$
$=(43\times10^{-6}/\cdot06)\times l/b.$

or, $l/b=\cdot0002\times\cdot06/\cdot000043=\cdot28$ or, $l=\cdot28\,b$.

Substituting for l, $\cdot28\,b^2=75$,

or, $b=16\cdot37$ cms.

Therefore, $l=75/16\cdot37=4\cdot58$ cms., *i.e.*

Length of shunt strip$=4\cdot58$ centimetres.

Breadth of shunt strip$=16\cdot37$ centimetres.

390. The Range of an Instrument :—

(*a*) *Ammeter.*—There are two methods for increasing the range of an ammeter (*a*) shunt, for direct current, and (*b*) transformers, for alternating current. An instrument, which when used alone will measure up to $\frac{1}{5}$th ampere, may be required to measure, say, 10, 50, or 100 amperes. This is obtained by using shunts of suitable values. Let the ammeter A have a resistance of r ohms, and let R equal the shunt to be used with the ammeter. If I_a is the current which, flowing in the ammeter alone, produces the full-scale deflection, and if v is the P. D. between the terminals of the ammeter, then I_s, the current through the shunt, will be v/R.

Also $I=I_a+I_s$, were I is the main current to be measured.

$\therefore R=v/(I-I_a)$, but $I_a=v/r$

$\therefore R=r\,I_a/(I-I_a)$.

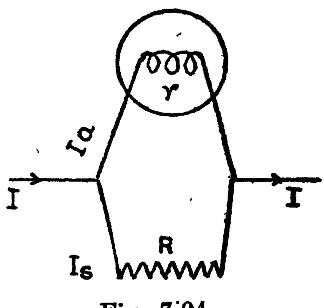


Fig. 7·04.

If we know the resistance r of the ammeter and the current I_a necessary to produce full-scale deflection when the ammeter is used without a shunt, the value R of the resistance of the shunt which must be used when the range of the instrument is to be increased to I amperes, can readily be calculated.

Example 11. The resistance of an ammeter reading $\frac{1}{5}$th amp. alone is 1 ohm, and that the resistance of the shunt increasing the range to 10 amperes is required.

Solution :—

$$R=\tfrac{1}{5}\times 1/(10-\tfrac{1}{5})=1/49 \text{ ohm.}$$

In ammeters of ranges below 10 amperes, the shunts are commonly mounted inside the instrument case. For ranges of 10 to 500 amperes, the shunts may be either internal or external. For still larger ranges, external shunts are always employed on account of their bulk and heat to be dissipated

(*b*) *Voltmeter.*—There are two methods of alternating the range of a voltmeter (except electrostatic voltmeters) :—(1) by connecting a high resistance in series with the instrument, (2) by what are called the potential transformers.

Let r be the resistance of a voltmeter, and R the value of the resistance connected in series with it. Let V_v be the P. D. between the voltmeter terminals, which gives the full-scale deflection, and I_v the current which then flows through the voltmeter.

Then if Vr is the P. D. across the series resistance, and V the P. D. between A and B, which it is required to measure—

$$V=Vr+V_v$$
$$=I_vR+I_vr.$$
$$R=V/I_v-r, \text{ but } I_v=V_v/r.$$
$$\therefore R=(V/V_v)\,r-r.$$

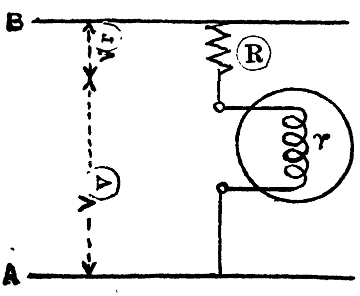


Fig. 7·05.

Example 12. A milliammeter of 4 ohms resistance which gives its scale deflection with 100 milliamperes is to be used as a voltmeter (*a*) reading up to 5 volts, (*b*) reading up to 200 volts.

Find the necessary resistances, and the power absorbed in each case.

(*a*) 5 volts must send 0·10 amp. through the instrument.

$\therefore$ total resistance $=5/\cdot 10=50$ ohms.

$\therefore$ resistance in series with instrument $=50-4=46$ ohms.

(*b*) Total resistance $=200/\cdot 10=2{,}000$ ohms.

$\therefore$ series resistance $=2{,}000-4=1{,}996$ ohms.

In each case the current at full scale reading is ·10 amp.

$\therefore$ in case (*a*) power absorbed $=5\times 0\cdot 10=\cdot 5$ watt.

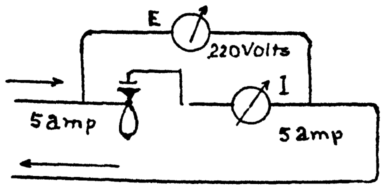
In case (*b*) power absorbed $=200\times 0\cdot 10=20$ watts.

Example 13. Suppose that a voltmeter has a resistance of 1 ohm, and that its maximum reading, when used alone, is $\frac{1}{5}$ volt. If this voltmeter is required to read up to 100 volts, the series resistance r to be added will be—

$$R=(100/\tfrac{1}{5})\ 1-1=499 \text{ ohms.}$$

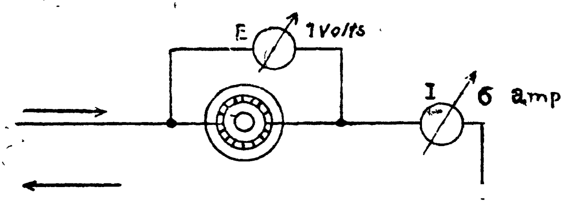
(*c*) *The Range of Wattmeters* :—The range of electro-dynamometer type of wattmeter may be changed by connecting multipliers in series with the voltage coil, or shunts in parallel with the series coil on direct-current circuits and low voltage, low frequency alternating currents. Where the wattmeter is to be used on high-voltage alternating-current circuits, transformers are used.

391. Correct Method of Connecting Instruments :—



Measuring low current and high voltage.

Fig. 7·06.

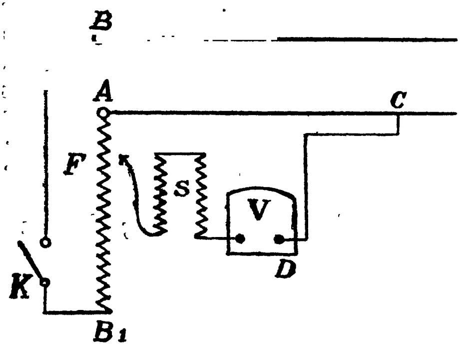


Measuring large current or low voltage.

Fig. 7'07.

***392. The Televoltmeter**:—It is used in measuring the voltage at the far end of the line. Where the system of distribution is by underground cable the far end voltage is measured by taking pilot wires—which are some strands in the cable insulated from others. Such pilot wires are not used in overhead systems or their use is restricted to few dozen yards.

AB represents the terminals at the generating end of the line. Measure accurately the resistance R of the line (out and home). Insert into one of the lines a resistance R/m, where m is the multiplying factor of the voltmeter V, corresponding to the series resistance S. Instead of adding the resistance R/m to a line, a length of line, say, AC, may be used instead of a pilot wire CD being brought back to the voltmeter. The



Televoltmeter.

Fig. 7'08

* Prof. Gisbart Kapp.

length of the pilot wire is only 1/250 part of the distance of the far end when the multiplying factor is 500. A potential coil AB_1 is attached to the home terminals and a tapping at F is so chosen that $AB_1/AF=m$. The P. D.s between the various points are in the following ratios; the letters corresponding to higher potential being put first.

$$AC=AD=IR/m.$$
$$AF=E_1/m.$$
$$DF=E_1/m-IR/m=(E_1-IR)/m=E/m.$$

DF is the voltmeter reading and, since m is the multiplying factor, the far end voltage is indicated on this voltmeter To find the exact position of the tapping point F we make a test when no current is flowing into the line. In this case the generator voltage is the same as shown by V.

All we have to do, then, is to shift the point of attachment of the voltmeter lead on the potential coil until V shows the home voltage. The potential coil AB_1 need to be calibrated; it is not even necessary to know its resistance accurately. All we care about is that the current passing through it shall be sufficiently large, say, of the order of an ampere, so that the small current taken by the voltmeter shall not sensibly disturb the potential gradient along AB_1. To prevent waste of energy a key K may be inserted. If the attendant wants to take a reading, all he has to do is to depress this key.

Example 14. Show how to construct a C. C. voltmeter, which, when connected to the mains in the generating station, will indicate the P. D. at the far end of a feeder.

A station voltmeter if connected to a 550-volt D. C. circuit as shown in the figure 7'09. The total resistance of the transmission line is R_0. R is a low resistance connected in series with the line and a high resistance (r_1+r_2) is connected across the line. The voltmeter resistance is r. If the current taken by the voltmeter is negligible compared with the load current only, show that the voltmeter will indicate the voltage at the load L if r_1 and r_2 are in the correct ratio. What is

this ratio in terms of R and R_o ? If the voltmeter has a 60-volt scale and a resistance of 5,680 ohms and if the line resistance R_o is 0·18 ohm and R is 0·02 ohm, what must r_1 and r_2 be so that the voltmeter will be direct-reading, *i.e.*, the voltmeter reading of 50 indicates 500 volts at the end.

Voltage at the generating station=550 volts.

Resistance of the lead and return of the transmission line=R_o ohms.

Low resistance in series with the line=R ohms.

High resistance connected across the line $=(r_1+r_2)$ ohms.

Total resistance in the line (transmission) $=(R_o+R)$ ohms.

If I is the load current and if

$$R=\frac{R+R_o}{K} \text{ or, } K=\frac{R+R_o}{R}$$

then, voltage drop in the line=$I\,(R+R_o)$

$$\text{Voltage drop across } AC=I\left(\frac{R+R_o}{K}\right)$$

$$=I\frac{(R+R_o)}{\dfrac{R+R_o}{R}}$$

$$\text{The current flowing through } AB=\frac{550}{r_1+r_2} \text{ amperes.}$$

$$\text{Voltage drop across } AD=\frac{550}{r_1+r_2}\times r_1$$

$$=\frac{550}{\dfrac{r_1+r_2}{r_1}}$$

$$\text{Then, voltage drop across } CD=\frac{550}{\dfrac{r_1+r_2}{r_1}}-\frac{I\,(R+R_o)}{\dfrac{R+R_o}{R}}$$

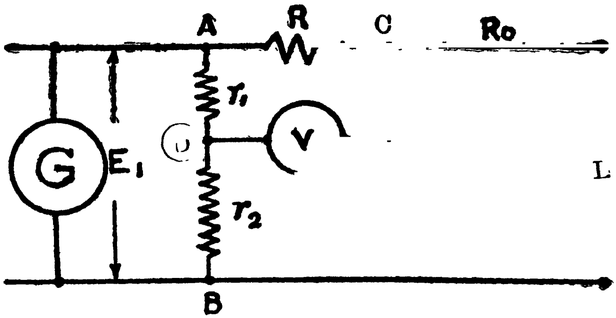


Fig. 7·09.

Now, if $\frac{r_1+r_2}{r_1}=\frac{R+R_0}{R}=K$

Then voltage drop across $CD=\frac{1}{K}\left[550-I\,(R+R_0)\right]$

Where $550-I\,(R+R_0)$ is the voltage at the load.

The voltmeter will indicate the voltage at the load if

$$r_1 : r_2 :: R : R_0$$

$$\frac{r_1+r_2}{r_1}=\frac{R+R_0}{R}=\frac{\cdot 2}{\cdot 02}=10$$

$$\frac{\text{Voltage at load}}{\text{Voltage reading in the voltmeter}}=\frac{500}{50}=10$$

Voltage drop across $AD=\frac{550}{10}=55$ volts.

To find resistance r_1 of AD

$$\frac{55}{50}=\frac{r_1}{5{,}680}$$

$$\therefore\ r_1=\frac{55\times 5{,}680}{50}=6{,}248 \text{ ohms.}$$

Then, $\frac{r_1+r_2}{r_1} = 10,$

Or, $r_1 + r_2 = 6{,}2480$ ohms.
Or, $r_2 = 62{,}480 - 6{,}248 = 56{,}232$ ohms.

393. Voltmeter Compensator :—In an alternating-current circuit the voltage between transmission lines at some remote feeding centre or receiving station is indicated by the voltmeter in the central station by the voltmeter compensator. *G*, the alternator, delivers alternate current *I* at the pressure *E* between its terminals which is transmitted over a line. The resistance of the line including *r* is *R* and the reactance including *x* is *X* and the voltage at the receiving end is E_t. The loss of voltage due to resistance is *IR* and that due to inductance is *IX*.

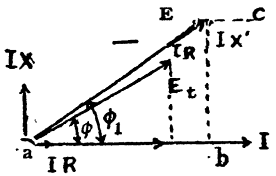


Fig. 7·10.

The relation between E_t, *E*, *IR* and *IX* is shown in Fig. 7·10 in phase with *E*.

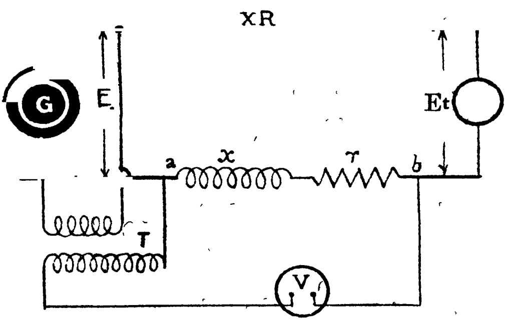


Fig. 7·11.

Now the transformer *T*, Fig. 7·11, supplied the voltage in phase with *E* to the voltmeter *V* and say one-tenth as great, and let $x=X/10$ and $r=R/10$, then the voltage between the points *a* and *b* consists of two parts, *Ir* and *Ix*, which are in phase with, and one-tenth as great as *IR* and *IX*, respectively.

$\therefore E/10-(Ir+Ix)=X/10$ (vectorially) and they are in phase with each other. Hence, the voltmeter reading

being acted upon by $(E/10)-(Ir+Ix)$ gives the reading which multiplied by ten is equal to E.

Modification, as shown in Fig. 7·12, is made in case of high-voltage mains, where T' is the current transformer and T is the step-down potential transformer in the case, containing the resistance r, and the reactance x, and upon which the dial switches are mounted. VR is the resistance in series with the voltmeter.

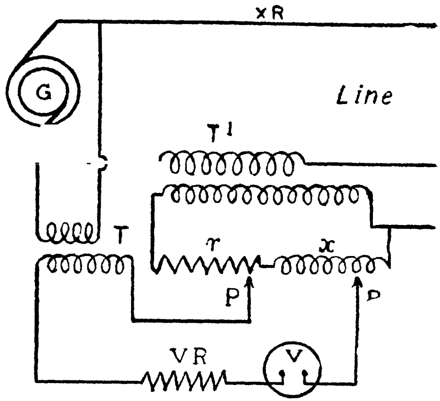


Fig. 7·12.

394. Peak Voltage and its Measurement by Sphere and Needle Gaps :—One of the simplest methods of obtaining a measure of the value (maximum value in the case of alternate current) of a high voltage is to determine the length of air-gap between two electrodes across which the given voltage will just cause a spark to pass. The voltage required to break down such a gap depends upon : (1) The shape and size of the electrodes ; (2) the presence of other conductors in the vicinity of the gap ; (3) the time of application of the voltage ; and (4) upon the temperature and pressure of the air. The dependence of the break-down voltage upon the shape and size of the electrode is due not only to the effect of these factors, and upon the potential gradient in the gap but also to the fact that the maximum potential gradient at which air breaks down is dependent upon the distribution of the electrostatic field in the gap and is greater for very short gap (0·5 cm. of less) than for long gap.

For the same maximum value of the voltage it has been found that the striking distance is independent

of the wave shape and frequency, and is the same for direct as for alternating voltage.

395. Time of Application of Voltage :—Air (and other gaps) will stand for a short period of time, *i.e.*, a few seconds) ; a much larger potential than it will stand for an indefinitely long period of time ; this phenomenon is known as dilatation. After a voltage has been applied to a gap for about one minute, the apparent dielectric strength becomes sensibly constant. When measurements must be made with great rapidity, dilatation may be prevented by illuminating the gap by an arc-lamp. This procedure reduces the value of the sparking voltage, but only to a slight extent.

396. Needle Point and Spark Gap :—The needle point gap was for many years the standard method of measuring high voltages, but it is unsatisfactory for very high potentials because of variations due to atmospheric pressure, humidity, proximity of surrounding objects and sharpness of the needle points. Spheres are now used instead of needle points for the higher values. A gap with carefully machined and polished spheres gives very reliable and consistent results due to the fact that the gap breaks down before corona forms, resulting in a negligible dielectric spark lag. The A. I. E. E. standards recommend the use of the sphere gap for voltages above 50 K. V. and preferably down to 10 K. V. The needle gap may, however, be used from 10 K. V. to 50 K. V.

397. Ground Detectors :—The connection between a current carrying conductor and the earth which materially reduces the normal insulation resistance of the line is usually detected by lamps or special form of voltmeters or static ground detectors operating on the same principle as electrostatic voltmeter. One form of ground detectors of the direct-current type has two coils differentially wound on the moving system, one end of each coil is connected to the ground and the two free ends are connected respectively to the two sides of the system. If the lines are equally insulated, the pointer stands at the centre of the scale, in normal equilibrium, when the ground or fault occurs, current flows through the

coil connected to the ungrounded side producing a

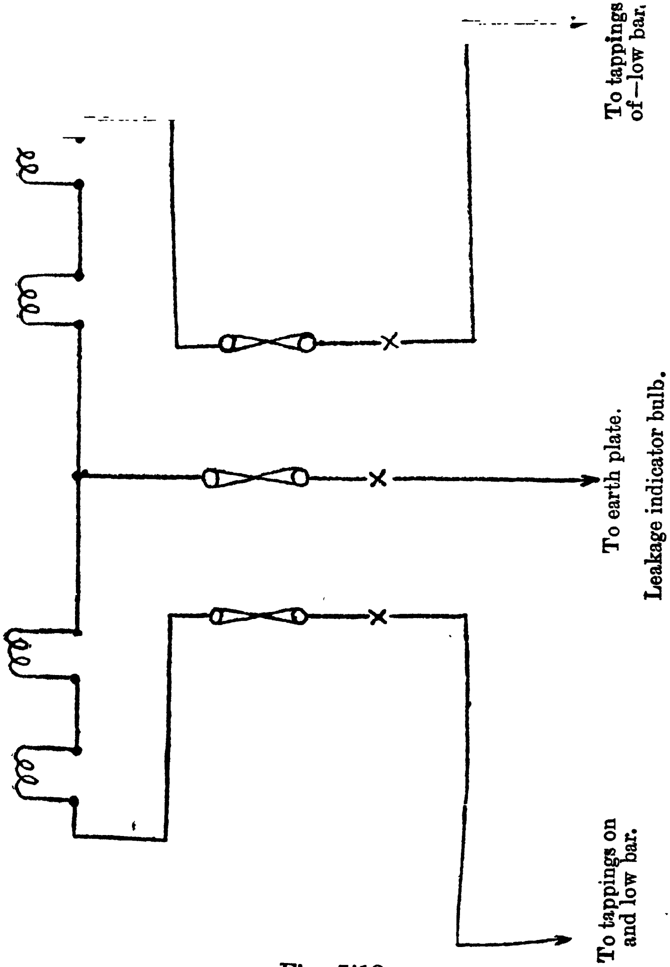


Fig. 7·13.

deflection of the pointer. In the static ground detector

the equilibrium of the forces acting on P is destroyed if the lines are not equally insulated and P is deflected to M or N which is connected to the line having the better insulation, the force of deflection being proportional to the relative resistance between the lines and the earth. The movable vane P is connected to the earth, fixed plates M and N are connected, one to each of the two mains.

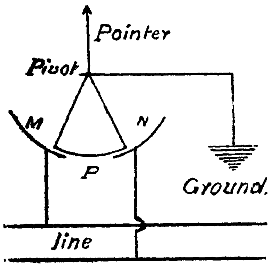


Fig. 7·14.

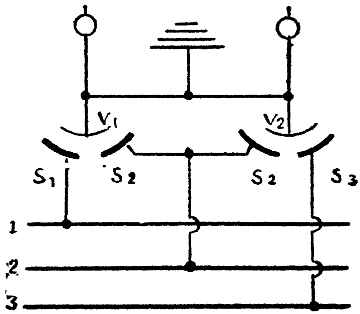


Fig. 7·15.

The *static ground detectors* are always operated through condensers or high-resistance rods of graphite so located that the wiring is short and the conductors properly separated and far enough from neighbouring metal so as not to interfere with the operation of the instruments.

Two single-phase detectors will work satisfactorily on three-phase circuits if the junction point of the two instruments is connected through a condenser to the third line wire (Fig. 7·14).

It is a good practice to have the ground detectors in the switchboard, to indicate between any line and earth any serious reduction of insulation resistance.

For normally-grounded systems an ammeter showing the leakage current is connected to earthed circuits between the earth plate and the system. To protect the

instrument from excessive leakage current short-circuiting devices are used which operate when the current reaches a predetermined value.

398. Electricity Supply Meters:—There are really five conditions pertaining to the systems of distribution of electrical power, and these give rise to as many different ways of measuring or charging for the energy supplied.

No.	*Working Conditions of Circuit.*		Quantity Measured.	Name of Meter.
	Constants.	Variables.		
1	*I. V. t*	*o*	*o*	None.
2	*I. V.*	*t*	$\int_{t_1}^{t_2} dt$	Time check or hour counter.
3	*I*	*V. t*	$\int_{t_1}^{t_2} V.\,dt$	Volt-hour meter.
4	*V*	*I. t*	$\int_{t_1}^{t_2} I.\,dt$	Coulomb, or amp-hour meter.
5	*o*	*I. V. t*	$\int_{t_1}^{t} I^2\,V.dt$	or watt-hour meter

Where I and V=instantaneous values of current and voltage, t_1 and t_2 being the initial times between which the energy is used, and, therefore, requires to be measured, and dt, a very small interval of time.

An elecrictity meter, therefore, is an integrator of the variable quantities in a circuit.

No. 1 is the case when no meter is used, the consumer is charged by contract under the distinct understanding that he only uses the lamps for the usual length of time each day.

No. 2 is used in case of motors or arc lamps, etc., running on constant load, where the electrical power supplied to them is constant, only the remaining factor of the energy, time, being measured.

No. 3 is for series systems at constant current.

Nos. 4 and 5 are used with parallel system of distribution.

Instruments classed under No. 5 subdivide into various forms as follows:—

Without Clocks:—	Chemical. Motor. Thermal.
With Clocks ...	Periodic integrator. Continuous integrator. Clocks affected.

The thermal form of meter has become obsolete, as it is to be very delicate to reduce frictions to a minimum owing to their small driving torque and there is waste of energy.

A great disadvantage in this type of meter is the large amount of energy wasted in it.

399. Some Requisites of a Good Meter:— An electricity meter is essentially a commercial apparatus. It must be capable of often standing comparatively *rough treatment*, and at the same time must possess the accuracy of a *laboratory instrument*. The most important points which must be seen in a good meter are simplicity, cheapness, accuracy, permanency of calibration, reliability of working, low internal losses, independence of temperature variations, freedom from external mechanical and magnetic disturbances, absence of creeping, *i.e.*, shunt running (this latter condition applies only to watt-hour meters); low starting current and large overload capacity. It should be light, portable, and of sound mechanical construction. If greater complexity ensures greater accuracy and reliability

and wider range, other conditions remaining unaltered, and cost be not materially increased, it should not be rejected only for its complexity of structure.

A meter should require no attention beyond that of taking the dial readings once a quarter ; consequently, it should not be too delicate or fragile, and should be capable of being sealed by the supply company in a dust and water-tight case, to prevent it being tampered with by the consumer.

Moreover, the internal parts should be all enclosed in a case of iron, so to be shielded from external magnetic influence, (by magnetic shielding).

All current-carrying parts of a meter should be highly insulated from one another and from earth. The constant of an energy meter should not be appreciably altered by voltage fluctuations not exceeding 10 per cent. below or above the normal pressure. In the case of an alternating-current energy meter the constant is, in addition, dependent on the frequency of the supply current, and it should not be appreciably altered by a ten per cent. increase or decrease in the normal periodicity of the circuit.

In all cases meters should be capable of starting with the current taken by the smallest lamp used in practice, and should read accurately over their entire range, as a small error may amount to much in the year.

Meters possessing fine-wire circuits are liable to the temperature error met with in voltmeters—an error which can be minimised in the manner mentioned before. Copper being always used in coils, this error, within the usual limits of temperature, may amount to 6 per cent. or more.

***400. Selection of the Meter** :—The selection of a meter depends on local conditions, the nature of the supply current, whether continuous or alternating, the voltage, the function of the meter, the class of consumer, price, guarantee, shunt losses, and probable cost of maintenance and repairs.

* Salmon's Electricity Meters.

In the case of a continuous-current supply at approximately constant pressure, from considerations of initial capital outlay, the annual loss in the pressure circuit of an energy meter, maintenance, depreciation and interest charges, the *ampere-hour* meter is decidedly to be *preferred to the watt-hour* type especially in the case of small consumers, whose actual bill may not be a very large one, but who are amongst the most profitable class of cosumers to a supply station. The ampere-hour meter is calibrated to register the units consumed at the declared voltage of supply, on the assumption that the voltage is kept constant. It is unaffected by voltage variations, so that, if the pressure across the circuit to which it is connected be above the declared value, a loss of units is incurred due to its use. Some circuits will have their voltage above the normal, and with ampere-hour meters there will be a loss; others will be at the correct voltage, and there will be neither loss nor gain; on the other hand, there will be a gain, in other circuits across which the voltage will be below its right value, so that in this case there will be a distinct gain. On the whole, in a well-designed system of distribution a very fair balance will be obtained. If the ampere-hour meter register U units in the year, on the assumption that the voltage V is constant, whereas it is always 2 per cent. above this value, then the loss to the station is $\cdot 02 V \times U \times d$, where d is the selling price per unit. If the voltage be low instead of high, and by the same amount, this result will represent the gain to the station.

The question to be decided with ampere-hour meters is whether they shall be of the *electrolytic or motor type*. *Electrolytic meters* have the advantage of being cheaper than motor meters, but they certainly require more attention, as they have to be either reset or refilled after definite periods; they are more or less unmechanical, and do not comply with the general conditions of practice so satisfactorily as a well-designed motor meter.

Electrolytic meters, which are essentially *Coulomb meters*, commence registering with currents far less than is required for the smallest lamp made; and this is one

of their great advantages. They are also the simplest and are free from errors due to friction which accrue to motor meters.

Clock meters register correctly, however small the current may be; they have a wide range and a high degree of accuracy, but are expensive and somewhat complicated. For special purposes they are particularly well adapted, and the three-wire type correctly measures the energy taken in a three-wire direct-current or single-phase alternating-current network, whatever be the distribution and nature of the loads on the two sides of the system. This is not the case with the ordinary three-wire energy motor meter, which correctly registers the energy in such a system under certain conditions only.

When the supply is an alternating current, the meter used invariably measures electrical energy, and the relative shunt losses play a very important part in the selection of the meter, besides its actual cost. The performance of the meter on inductive loads is one which also must not be lost sight of, especially if in the circuits a phase displacement between the current and the pressure be likely to occur. In fact, all meters intended for alternating-current supply circuits should be suitable for inductive loads, whether the loads be so or not. As already mentioned, the meters for such circuits are on the induction principle, and only these should be used, on account of their simplicity, ease of adjustment, low cost and low shunt losses relatively to commutator motor meters without iron, their considerably smaller frictional resistances to motion, the total elimination of brush friction and commutators, or rubbing contacts of any description, and the absence of any current from the supply circuit in the revolving armature, which is simply a disc or cylinder of aluminium or copper.

Motor meters are not so sensitive owing to the larger amount of friction to be overcome. This results in an uncertainty of action in starting, and may mean that two or three lamps can be used alone, and for nothing, without the meter starting.

This friction is practically the only serious trouble met with in this class of meter, and it both limits the accuracy and causes wear and tear of the rubbing parts, in addition to the loss of energy.

401. Capacity of a Meter:—The capacity of a meter is generally dependent on the maximum capacity of the installation in which it is placed It seems, however, advisable to use meters having a smaller capacity than the maximum of the circuits it controls, and to have a relatively large overload capacity, the degree of which varies with the nature of the load of the particular circuit to which the meter is connected. As a general rule, a house-service meter works mostly in the region of 20 to 30 per cent. of full load, and is, therefore, not working at the best part of its curve, as usually, the least error occurs between half and full load. The full load of an electric lighting installation in a private house is only taken on special occasions. which are not of frequent occurrence, so that, if the capacity of the meter be, in such a case, made to correspond to half the maximum number of lamps installed, and be capable of carrying a large overload current for short periods, it would be much more efficient, would probably cost less, and would be mainly operating near its full-load capacity The meter should, consequently, be less dependent on the variable nature of friction at low load, and start working when only one or two lamps are switched into circuit. A meter should, with reference to its starting current, register with certainty the minimum load of the circuit to which it is connected.

402. Watt-Hour Meter:—A watt-hour meter consists essentially of (1) a small electric motor, which may be either of the commutator type, mercury and disc type or induction type, (2) a brake system composed of a non-magnetic material (usually copper or aluminium) mounted on the armature spindle and so arranged that its edge rotates between the poles of one or more permanent magnets, and (3) a system of gears with numbered dials forming a suitable registering mechanism for indicating the number of revolutions of the armature or disc. One winding, called the potential coil, is connected across,

either directly or through suitable instrument transformer in shunt with the load and the other winding, called the current coil, is connected in series with the load, the connections being the same as for an indicating wattmeter.

Principle of Operation :—Motor type meters are so constructed that the average torque exerted by the motor is proportional to the average power taken by the load. The brake system is so designed that the opposing torque, due to the eddy Foucault currents induced in the disc as it rotates between the poles of the permanent magnets, is proportional to the speed of the disc. When the disc acquires a given speed, the driving torque must be just equal to the opposing torque, and must, therefore, be proportional to the speed. Hence, the speed of the disc is proportional to the average power, and, therefore, the total number of revolutions, which the disc makes during any interval, must be proportional to the total energy input during this interval, whether the power remains constant or varies. To determine the energy input to the load in watt-hours or kilowatt-hours it is, therefore, only necessary to take the difference between the dial readings at the beginning and end of given interval, and multiply by the proper constant if the meter is not direct-reading.

Sources of Error :—In a D. C. watt-hour meter the chief sources of error is the friction of the brushes (which is more or less variable), friction of the bearings of the motor and gear train, and air friction, the brush friction being by far the most important. In A. C. watt-hour meters, the lack of exact 90° phase relation between the impressed voltage and the magnetic flux due to the current in the potential coil may cause additional errors which vary with the frequency, power factor and also with the distortion of the wave form ; in modern meters these errors are practically negligible. Instrument transformers, unless properly designed, introduce additional sources of error. Devices and methods of overcoming, or correcting these errors are described below.

Classification According to Service :—Watt-hour meters may be classified according to the service in which

they are used, *viz.*, (1) house meters for use in residences or factories, (2) switchboard meters for use in central stations, (3) meters for use in the individual power installations and isolated plants. Meters for house service are generally front-connected, separately-sealed devices which can be installed and sealed to prevent tampering. Switchboard meters are generally back-connected and of such design as to match other switchboard devices. "Meter-boards," equipped with the necessary auxiliary or protective devices, are frequently used with house meters, in order to insure proper connections and sealing.

403. Commutator Type of Watt-hour Meter:—The commutator type of meter is now used only for direct-current circuits, although before the induction meter was so highly perfected large numbers were used for alternating current as well as for direct current. The motor consists of a set of stationary coils, commonly called field coils, which carry the current, and an armature wound with small wire which is connected across the terminals of the load or in shunt with the supply circuit ; generally, a series resistance is used to absorb parts of the line voltage. The connection to the armature is by a commutator and brushes, as in an ordinary commutator type of shunt motor. Special attachments are sometimes added for very large capacities, such as double armature astatically arranged, and damping magnets enclosed in a laminated iron shield in order to reduce strong-field errors where heavy currents are used and heavy short circuits are frequent.

It should be noted that the operation differs from that of an ordinary shunt motor in that the speed increases with increase of field strength, since its back E. M. F. is much less than 50 % of the line voltage.

On account of the inductance of the windings of the commutator meter, it does not record accurately on A. C. circuits unless properly compensated, the error being greater, the less the power factor.

404. Compensation for Friction ; Light-load Adjustment:—Friction in a well-designed watt-hour-meter will be very small and will be noticeable only on light loads of 10 per cent. and below. Te compensate for

this friction, a "light load adjusting coil" is added, which is an auxiliary or compounding coil. This light load coil is connected in series with the armature It is placed adjacent to the field coils so that its field strengthens the main field and produces a slight torque independent of the power and just sufficient to compensate for friction.

Details of Construction, Bearings, etc.:—In the design of the modern direct-current commutator-type of watt-hour meter, great thought has been given to the mechanical construction in order to obtain small air-gap between the armature and field coils, light weight armatures and field coils, light weight armatures and commutators and brushes which will have very small friction and yet stand the wear and carry the current to the armature without undue sparking and pitting of the contact parts. In a watt-hour meter of the most approved design the field coils are wound with enamelled copper strips and the armature wire is enamel-covered wire wound on a paper sphere mounted on a spindle of light steel tubing. The lower bearing carries all of the weight and the upper bearing is a guide bearing, as all meters have vertical shafts. The lower bearing consists of a steel pivot mounted in the end of the spindle or armature shafts, running on a jewel bearing. In most cases, a good grade of sapphire is used for the jewel and is cupped and polished so as to provide a bearing with as little friction as pssible. Of late years a great deal of attention has been given to the bearings and in some cases, particularly on high-capacity meters with astatic armatures and a correspondingly heavy weight, diamond jewels are being used with excellent results. The diamond jewel will last much longer than the sapphire before wearing sufficiently to increase the friction and thereby change the accuracy of the meter, particularly at light load.

405. Capacity of Commutator Watt-hour Meters:—Commutator-type direct-current meters are built in capacities ranging from 5 to 10,000 amperes, 100 to 600 volts. Meters of this type are furnished with double-current circuit for three-wire circuits, the maximum ampere capacity for three-wire meters being 6,000 amperes.

Special meters have been supplied for 1,200 and 2,400-volt railway circuit.

Accuracy:—Tests on direct-current commutators show that a meter of good design should start on two per cent. of full load and should give accuracies about as follows:—To within $3\frac{1}{2}$ per cent. from 5 per cent. to $\frac{1}{4}$ load, 2 per cent. from $\frac{1}{4}$ to full load

406. Mercury-Motor Watt-hour Meter:—The mercury-motor watt-hour meter has been manufactured for both alternating and direct current as the induction type of meter has been found superior for alternating current. The motor element consists of a mercury well or reservoir in which is partially floated a metal armature disc or drum, usually of copper. The chamber is filled with mercury and fitted with non-spillable opening at the top through which the spindle is attached. The main current is led into the mercury by means of electrodes, and since mercury has about forty times the resistance of copper, the major part of the current traverses the armature disc or drum, passing out through the mercury to the opposite electrode. The potential or shunt coil is wound with many turns and is mounted on a laminated iron core so placed that the flux set up will cut the armature disc or drum.

The torque exerted on the disc or drum is proportional to the product of the current through the disc and the current in the potential coil, and, therefore, to the power supplied to the load. A brake system similar to that used in the commutator type of watt-hour meter renders the speed proportional to the torque and, therefore, to the power supplied to the load.

407. Compensation for Friction, Light Load Adjustment:—For compounding or light-load compensation for friction a thermal device is used in some cases, and it is also possible to obtain compensation by shunting part of the potential circuit through the armature disc. The thermal device employed is a thermo-couple shunted around the mercury chamber, and heated from a resistance coil connected across the line The small current generated in the thermal couple forces a slight current through the armature and produces a compounding effect.

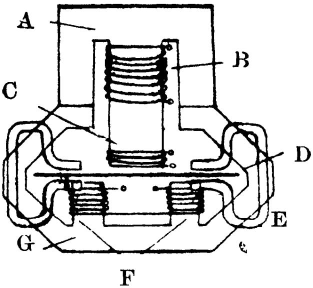
408. Application of Mercury Meters:—Mercury motor meters, on account of the low resistance of the current circuit (disc or drum), are particularly well-adapted for use with external shunts, since but a small potential drop in the shunt is required. They are, therefore, used in large numbers for switchboard work where large currents are used and where external shunts can be conveniently installed.

409. Details of Construction:--The several designs of the mercury motor meters on the market differ in mechanical construction and in methods for obtaining light load adjustments. The chief difference in mechanical construction is in the motor element, where a mercury chamber of non-metallic compound is used in some cases, and a general silver chamber enamelled on the inside in other designs. Armatures differ in that some designs use a copper disc and others a copper drum or thimble.

410. Capacity of Mercury Watt-hour Meters:—Direct-current mercury meters are in themselves independent of ampere capacity, as external shunts are used. Shunts giving a capacity as high as 60,000 amperes have been furnished. Meters designed for voltages up to 600 volts can be furnished without any difficulty and special meters have been supplied for 1,200 and 2,400-volt direct-current railway circuits.

411. Accuracy:—The light-load accuracy of a mercury-meter may vary on account of varying friction of the armature disc in the mercury, and there is an overload drop in the accuracy curve due probably to heating of mercury and a slight buckling of the armature disc by the current. Modern mercury motor meters have an accuracy curve much nearer a straight line. The mercury meter also shows hysteresis errors due to the fact that the iron is used in the potential circuit. For this reason, the meter shows a small difference in reading when the voltage is raised and then lowered even though through a comparatively small range. Direct-current mercury motor meters for house service should have an accuracy within the limits given for commutator meters.

412. Induction Watt-hour Meter :—This type of meter, the essentials of which are illustrated in Fig. 7·16, has a laminated soft iron core on which is mounted the current and potential windings. The current winding consists of a few turns of coarse wire, while the potential coil has many turns of fine wire. The flux due to the current coil is in phase with the load currents, and the flux due to the potential coil approximately in quadrature with the voltage across the load, since the potential is highly inductive. The poles from the two windings are arranged so that the armature disc passes between and is cut by the alternating flux due to each winding.



A Iron core
B Potentia coil
C Lag coil
D Armature dise
E Damping Brake or magnet
F Current coils
G Iron core

Fig. 7·16.

413. Principle of Operation :—There is thus set up in the disc currents which flow about each pole in approximately concentric circles, the induced currents due to the two windings being in quadrature for a load of unity power factor (approximately only, unless a suitable phase compensator is used). Part of the current induced in the current coil passes under the pole of the potential coil and, therefore, through a magnetic field, which is approximately in phase with this current, and similarly part of the current induced by the potential coil passes under the pole of the current coil and, therefore, through a magnetic field approximately in phase with it; for power factors less than unity the phase difference between these currents and the magnetic fields through which they pass is the same as the difference in phase between the load current and voltage. Hence, a torque is produced on the disc having an average value proportional to the load supplied through the meter.

414. Phase Compensation ; Lag Coil :—In order to make the induction watt-hour meter record correctly, especially for power factors less than unity, it is necessary to cause the flux at the tip of the pole to lag exactly 90 degrees behind the voltage impressed on the potential coil. A common method of securing this condition is to mount on the potential pole a short-circuited winding the resistance of which can be varied by a resistance wire soldered to the terminals.

415. Compensation for Friction ; Starting Plate :—The light-load adjustment can be obtained by placing a short-circuited loop of copper adjacent to the potential pole so that it can be shifted in a plane at right angles to the axis of the potential coil. This loop has induced in it currents which produce a field out of phase with the flux from the potential coil, and the reaction between these two produces on the disc a slight turning moment independent of the current in the current coil. The amount of compensation can be varied by shifting the position of the light-load coil, or starting plate, as it is sometimes called.

416. Details of Construction :—The induction-type of watt-hour meter is manufactured in several different types, all based on the same principle of operation but differing in mechanical construction and electrical characteristics. The general type of construction is to mount the iron core and windings on a metal frame, which carries the bearings for the armature, the core and windings being combined as a single unit in some designs.

Whereas in others the current and potential coils with their iron cores are mounted separately on a common frame or on the meter case. The other details of design consists of mounting the registering train and damping magnets and arranging the full-load, light-load and power-factor adjustments so that they are readily accessible.

417. Polyphase Induction Meters :—The polyphase induction meter in commercial use is nothing more than two single-phase meters with a common spindle

connecting the two armature discs. The measurement of the power with the meter is based on the two wattmeter methods for three-wire, three-phase and quarter-phase work, and a single modification of the two-element meter is used quite extensively for four-wire, three-phase work. The modification consists of a third current circuit by adding a winding to the current coils of both the elements. Such a construction is quite accurate except on badly unbalanced voltages, the most accurate arrangement for such work being three separate single-phase meters, or a single meter which contains three single-phase elements.

418. Capacity of Induction Watt-hour Meters :— Induction type meters are supplied in standard capacities ranging from 5 to 300 amperes both two and three wire single-phase and up to 150 amperes polyphase. Meters are generally used with self-contained potential circuits up to 600 volts, and for higher voltages and current capacities, potential and current transformers are used with 5-ampere, 110-volt meters. When transformers are used, either a multiplying constant for the dial alone can be used in connection with the ratio of transformation of the transformers, or the ratio of transformer can be included in the meter constant, so that the register is direct-reading with the transformers of proper ratio. For three-wire single-phase circuits it is possible to obtain special form of current transformer with double primary windings and a single secondary winding for connection to the meter.

419. Accuracy :—Modern induction watt-hour meters are susceptible of a higher degree of accuracy than the commutator or mercury motor meter. It is possible to obtain by special calibrations a combination of induction watt-hour meters and instrument transformers which will be accurate to within 1 per cent. over the ordinary range of commercial operation.

420. Prepayment Meters :—Standard watt-hour meters are sometimes fitted with a device whereby the circuit through the meter and load is closed only upon the insertion of a coin into the device and remains closed

only until a certain predetermined amount of energy has been recorded by the meter, when the circuit again opens automatically. When so equipped, the meter is called a prepayment meter The payment device may be either inserted in the watt-hour meter, or it may be placed in a separate attachment electrically connected to the meter.

421. Demand Indicator:—For sometime past various attempts have been made to inaugurate systems of charging for electrical energy which would be more equitable to both the consumer and the central station than a flat kilowatt or kilowatt-hour rate. The so-called "maximum demand" system has found favour with many and may find much more general application.

The system is based on the fundamental assumption that the charge to any consumer should be divided into two parts, one part fixed by the maximum power demanded by an individual consumer at any time during a certain definite period, and another part fixed by the total number of kilowatt-hours used during the same period.

422. Requirement of a Demand Indicator:—The kilowatt hours supplied to the consumer are readily measured and recorded by a watt-hour meter ; to record the maximum power (kilowatts) taken by the consumer various forms of "maximum demand indicator," usually called simply "demand indicators", have been devised. In the case of a practically constant D. C. voltage at the consumer's premises, a device which measures the maximum current is as satisfactory as one which measures maximum power, but when the voltage or power factor (in case of an A. C. system) varies, the maximum current indicator is not suitable.

In any case the device should be one in which the demand measured is not the instantaneous peak of the load demanded by the consumer, but is the average of the power demanded over an appreciable time interval, for the maximum demand recorded should not be influenced by short circuits, excessive current flow in starting motors, or by any abnormal consumption of energy that covers

too short a time to have any real effect on the capacity which must be provided in the central station to take care of the demand.

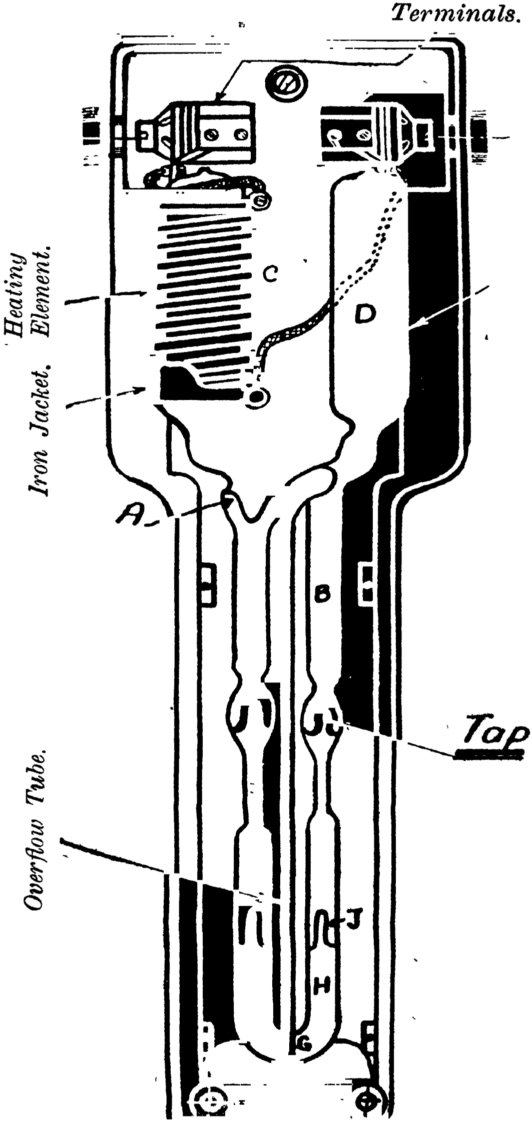
The time over which the demand should be taken differs with the character of the installation and its relation to the maximum power demanded and to the maximum capacity of the central station. In relatively large consumers installations the time should be carefully chosen with reference to the time that the central station can endure an overload successfully. In small installations such as residences, the time interval is not important, provided it is long enough to cover any abnormal and sudden fluctuation of load, but not longer than the ordinary period of sustained maximum load. In some instances, times as short as one or two minutes have been selected for large installations and about 15 or 30 minutes seems to be quite, generally, statisfactory for household installations and small industrial plants.

In connection with demand systems of charging it is sometimes of advantage to know at what time of the day the maximum demand occurs, for it is sometimes possible to give preferential rate to large consumers if they will draw their heaviest load at periods when the station load curve is below its maximum.

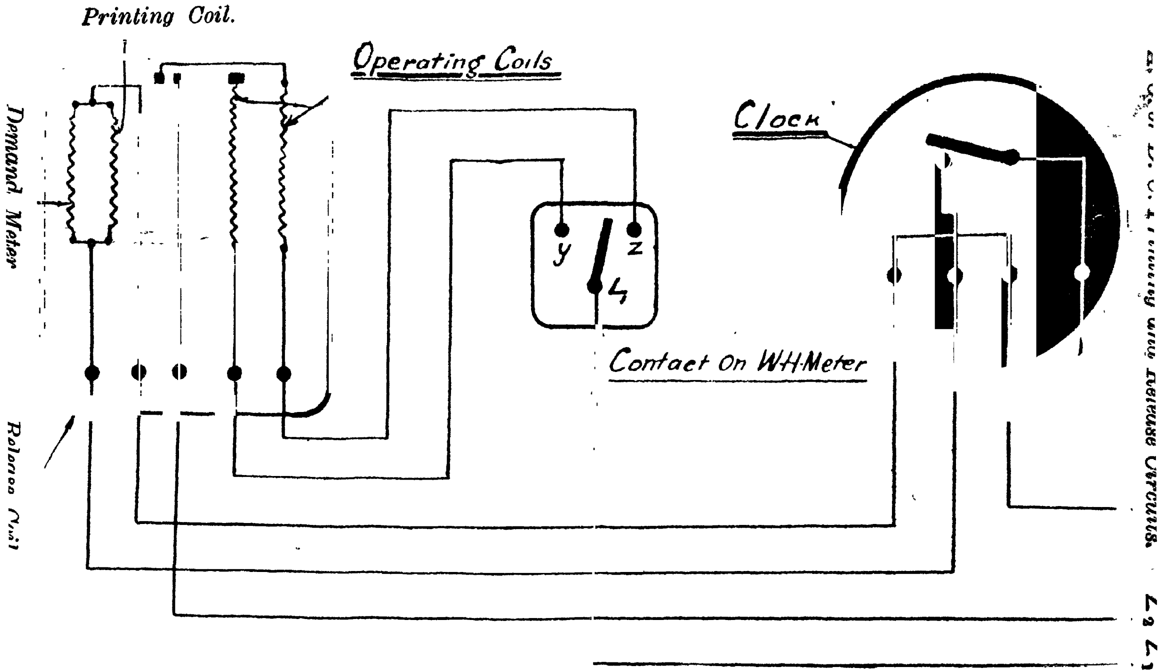
The general subject of demand indicators has received considerable attention within the past year or two and many new devices have been developed experimentally and will no doubt soon be on the market. The whole system of charging, including the necessary devices to be used, may be considered to be in a transition state. An indicator now in commercial use is briefly described below.

423. Wright's Maximum Demand Indicator :— This meter is mostly used on small industrial concern to whom power is supplied by power companies. The Fig. 7'17 shows a front view of this meter. It consists of a U-tube H-B connecting two air-filled bulbs *C* and *D*, which are closed at their upper ends. The U-tube contains a viscous fluid. The two bulbs are similar to each other, so that any change in the external temperature will not

To face page 576



Wright's Maximum Demand Meter



Back View of Demand Meter Connections.

alter the level of the fluid in the tube between them. One bulb C is heated by the passage of the current through the heating strip surrounding it and this drives the fluid in the direction of the other bulb D. Close to the bottom of D is an overflow leg or tube G, closed at the bottom end as the normal level of the liquid is up to the neck of this overflow ; any movement due to heating by the current will send some fluid down this, which will not return when the current ceases.

In order to prevent passage of air from bulb to bulb during transit there are a number of traps in the U-tube as indicated at E, J, etc. Sluggishness is ensured by the time taken by the bulb to heat up and by the viscosity of the fluid and narrowness of the tube. In some meters, it is further increased by introducing an iron jacket between the bulb and its heater so that a 5-amp. indicator, if connected, when cold, into a circuit carrying 5 amps., does not reach the 5-amp. mark until about $\frac{3}{4}$ths hour has passed, but if the instrument was warm due to, say, 3 amps. passing continuously, the rise to 5 amps. would, of course, be shown more rapidly. It will be continually making a running average over the consumption or is used for both A. C. and D. C. The resetting is quite simple and consists in unsealing the metal front and then tripping in the working position so that the liquid tapped in the overflow leg runs back to the U-tube.

Wright demand indicators of all capacities from 5 to 10 amps. inclusive may be connected directly into alternating-current circuit of any commercial frequency. Indicators of 200 amps. capacity and over are furnished with shunts for D. C. and with current transformers for A. C.

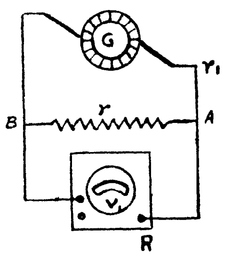
Disadvantage :—The wright demand indicator is not suitable for the determination of maximum loads in A. C. circuit of variable power factors. It leaves no record of the duration of the maximum demand, nor of the time at which it takes place. After the instrument has been reset, there is no original record of previous maximum demands.

Time Lag and Precision of Wright Demand Indicator :—Each instrument has its individual time lag and the same instrument may have different time lags at different loads. The time lag is shown by the following average figures : 90 % of any increase of load is indicated after approximately 4 minutes' duration, 97 % after 10 minutes, 100 % after about 40 minutes. Wright demand indicators are sufficiently accurate for most commercial instruments, provided they are installed in locations which are not subject to abnormal temperature variations.

424. Internal Resistance of Ammeters and Voltmeters :—Ammeters must have a low resistance, for they must absorb the minimum amount of voltage.

Importance of High Resistance for Voltmeter :—The internal resistance of a voltmeter must be as high as practicable so as to pass the smallest possible current and thereby not alter the potential difference between the points to which they are applied.

To prove the above, consider the following case :—Let G in the figure be a generator sending current through the resistance r ; and V a voltmeter indicating the pressure between the terminals A and B. There will be a certain difference of potential before the voltmeter is connected between A and B. This difference of P. D. will be less when the voltmeter is connected, owing to the lessening of the total resistance between the two points ; if the resistance of the voltmeter be high, this difference will be very small, and the higher it is the less the error.



7'18

In Fig. 7'18 let E be the E. M. F. of the generator, r the resistance of the circuit across A and B, between which the difference of potential is to be measured, r_1 the resistance of the leads, generator, etc., and R the resistance of the voltmeter.

Before the voltmeter is connected, the difference of potential between A and B is V.

$V=Ir$; $I=E/(r+r_1)$.

$V=r\ E/(r+r_1)$.

Joint resistance of r and $R=r\ R/(r+R)$.

$\therefore$ Total resistance of the circuit$=\{rR/(r+R)\}+r_1$
$=(rR+rr_1+Rr_1)/(r+R)$

$\therefore$ current $I'=E\ (r+R)\ /\ (rR+rr_1+r_1R)$

$\therefore\ V_1=\{E\ (r+R)\ /\ (rR+rr_1+r_1R)\}\times rR/(r+R)$

With the voltmeter connected, the difference of potential indicated by the instrument is—

$V_1=rRE/\ (rR+rr_1+r_1\ R)$.

The voltage across A and B is, therefore, reduced by the introduction of the voltmeter by the amount of

$V-V_1=rr_1V_1/(r+r_1)R$.

The error is

$P=100(V-V_1)/V_1=100\ rr_1/(r+r_1)R$.

The error is inversely proportional to the resistance R of the voltmeter.

Example 15 :—

Let $E=20$ volts,
$r=5$ ohms,
$r_1=2$ ohms,
$R=1{,}000$ ohms.

Solution :—

Then the reading of the voltmeter is

$V_1=20\times 1{,}000\times 5/\{(5\times 1{,}000)+(2\times 5)+(2\times 1{,}000)\}$
$=14{\cdot}26$ volts

and the error is

$V-V_1=5\times 2\times 14{\cdot}26/\{(5+2)1{,}000\}$
$={\cdot}0203$

and the percentage error is

$P=100\times 5\times 2/(5+2)\times 1{,}000={\cdot}143$ per cent.

If R be made 2,000 ohms, then

$V_1=5\times 2{,}000\times 20/\{(5\times 2000)+(2\times 5)+(2\times 2{,}000)\}=14{\cdot}27$ volts,

and the error is

$V-V_1=5\times 2\times 14{\cdot}27/(5+2)\ 2{,}000={\cdot}0102$

and the percentage error is

$$P=100\times5\times2/(5+2)\ 2{,}000=\cdot071 \text{ per cent.}$$

or just one-half the error with $R=1{,}000$ ohms.

If the error of measurement is not to exceed a stated per cent. P, then r and r_1 must be such that

$rr_1/(r+r_1)$ is less than $PR/100$.

If the circuit is closed by a resistance r_1, and it be desired to measure the E. M. F. of the generator by connecting the voltmeter between any two points as A and B, then $E=\{(R+r_1)/R\}\ V_1$, where V_1=reading on the voltmeter.

The error between the true value of the E. M. F. of the generator and that shown by the voltmeter is

$$E-V_1=r_1\ V_1/R$$

and the percentage error $P=100\ (r_1/R)$.

If the error is not to exceed P per cent., then the resistance of the generator, cables, etc., must not exceed $PR/100$.

For example, with a voltmeter having 20,000 ohms for 100 volts; if P must be less than 1/5 per cent., then r_1 may be as great as

$\frac{1}{5}\times20{,}000/100=40$ ohms.

*425. Measurements with Ammeter, and Voltmeter :—

Measuring Current with a Voltmeter :—If a known resistance be connected in series in a circuit and the voltage across the coil measured with a low-reading voltmeter, the current can be determined by Ohm's law.

A millivoltmeter is often taken for the purpose in which case a comparatively low-resistance shunt may be used, so that heavy currents may be measured without the shunt being disproportionately large—(Fig. 7·19).

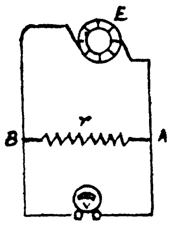
See that r has enough carrying capacity to avoid a rise of temperature which would change its resistance. If the reading is exact to $1/a$ volts, the measurement of the current will be exact to $1/a\times r$ amperes.

* Foster's Electrical Engineer's Pocket-Book.

II. Measuring Resistance with a Voltmeter :—

(a) General Methods.—

Let X in Fig. 7·20 be the unknown resistance that is to be measured, r a known resistance, E the dynamo or other steady source of E. M. F.



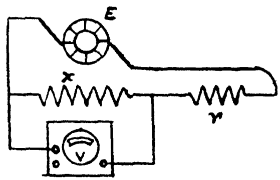


Fig. 7·19. 7·20.

Let the voltmeter reading be V; then connect the voltmeter terminals to r in the same manner and let the reading be V_1; then $X : r :: V : V_1$ and $X = r \times V/V_1$.

If, for instance, $r=3$ ohms and $V=6$ volts and $V_1=4$ volts, then $X=3\times 6/4=4{\cdot}5$ ohms.

If readings can be made to $1/q$ volt, the error of resistance measurement will then be

$$(100\times 1/q)\ (1/V+1/V_1) \text{ per cent.}$$

and for the above example would be

$$1\ (1/6+1/4)=0{\cdot}42 \text{ per cent.}$$

If there be a considerable difference between the magnitudes of the two resistances X and r, it might be better to read the drop across one of them from one scale, and to read the drop across the other on a lower scale.

(b) Measurement of Very Small Resistance :— Very small resistance can be measured with an ammeter and a millivoltmeter. This method is very convenient for measuring the resistance of busbars, the resistance of armatures, the drop being taken from opposite commutator bars and not from the brush-holder;

joints between conductors, switch contacts, brush-contact resistance and all switchboard appliances, the resistance of bound joints and other low resistances. As large a current as is available should be used.

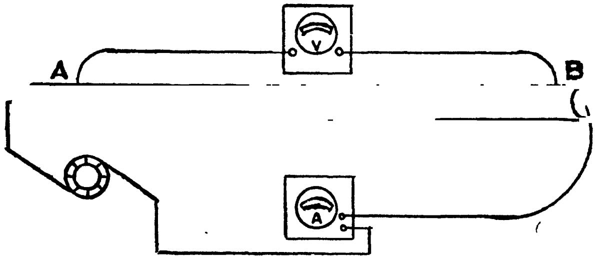


Fig. 7·21.

$X = V/I$

where, X=the resistance

V=drop potential between AB

I=current.

(c) Measurement of High Resistances :—With the ordinary voltmeter of high internal resistance, let R be the resistance of the voltmeter, X be the resistance to be measured. Connect them up in series with some source of electromotive force as in the Figure 7·22.

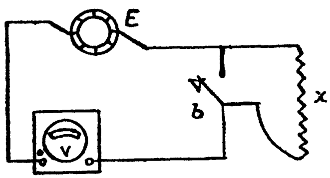


Fig. 7·22.

Close the switch b, and read the voltage V with resistance of the voltmeter alone in circuit ; then open the switch, thus cutting in the resistance X, and take another reading of the voltmeter V_1.

Then $X = R\ (V/V_1 - 1)$.

If the readings of the voltmeter be correct to $1/q$ of a volt, the error of the above result will be.

$\{100/V_1 q\}(V + V_1)/(V - V_1)$ per cent.

(d) Measurement of Very High Resistance :— Very high resistances require a very sensitive voltmeter which will give satisfactory results, for the reason that the reading V_1, when the switch b is opened, becomes so small with the ordinary voltmeter that the error is relatively very great. Instruments are on the market having a sensibility of 1,600 ohms per volt, or about 250,000 ohms for 150 volts.

Example 16 :—

If $X=1$ megohm and an ordinary voltmeter be used, $R=20{,}000$ ohms for 250 volts, and $E=220$ volts,

$$V_1 \text{ would be } \frac{ER}{X+R}=\frac{220\times 20{,}000}{1{,}000{,}000+20{,}000}=4{\cdot}3 \text{ volts};$$

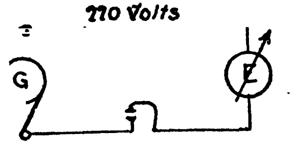
while if R were 250,000 ohms,

$$V_1 \text{ would be } \frac{220\times 250{,}000}{1{,}000{,}000+250{,}000}=44 \text{ volts},$$

that is, with the high-resistance instrument, with the same accuracy of the instrument scales, the percentage error is about 1/10 as great as with the lower resistance instrument.

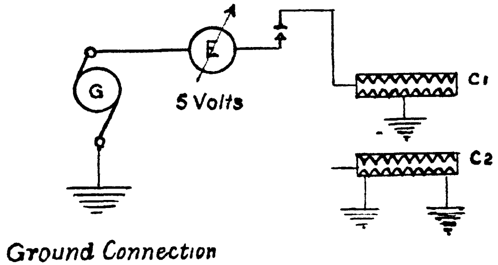
(e) Measuring the Insulation Resistance of Lighting and Power Circuits with a Voltmeter :— For rough measurements where the exact insulation resistance is not required but it is wished to determine if such resistance exceeds some stated figure, then a voltmeter of ordinary sensibility will answer. The methods, in general, are as follows :—

According as the direct or alternating current system of supply is used, a suitable type of voltmeter of known resistance preferably of high resistance and sensitivity, and a source of E. M. F. are necessary. First, the voltage of the E. M. F. source is taken, Fig. 7·23. The apparatus



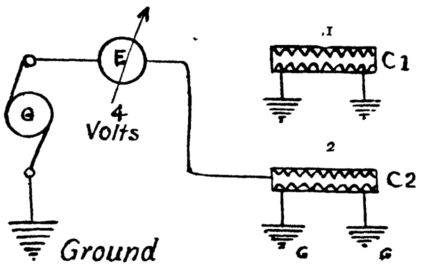
E. M. F. Reading.
Fig. 7·23.

is then arranged to measure the resistance from each side of the circuit to ground, Figs. 7·24 and 7·25. Then



Reading for Insulation Resistance of Conductor No. 1.

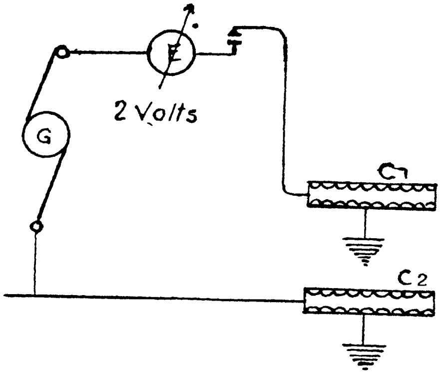
Fig. 7·24.



Reading for Insulation Resistance of Conductor No. 2.

Fig. 7·25.

connect the apparatus to measure the resistance between conductors as in Fig. 7·26.



Reading for Insulation Resistance between Conductors C_1 and C_2.

Fig. 7·26.

$X = R\,(V/V_1 - 1)$,

Let X = insulation resistance to ground as in Fig. 7·27,
X_1 = insulation resistance to ground of opposite lead,
R = resistance of voltmeter,
V = potential of dynamo E,
V_1 = reading of voltmeter, as connected in Fig 7·27,
V_2 = reading of voltmeter, when connected to opposite leads,

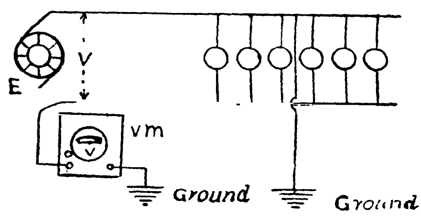


Fig. 7·27.

Then $X = R\,(V/V_1 - 1)$,

and $X_1 = R\,(V/V_2 - 1)$.

More correct approximation can be made by taking into account the fact that the path through the resistance R of the voltmeter is in parallel with the leak to ground on the side to which it is connected as shown in the Fig. 7'28.

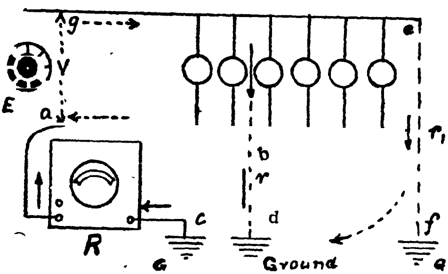


Fig. 7'28.

In this case the voltage V of the circuit will not only send current through the lamps, but through the leaks $e\ f$ to ground, and through the ground to d and c, thence through r to b, and c to a; these two last paths being in parallel, therefore, having less resistance than if one alone was used: thus if r be the resistance of the ground leak rb, and r_1 be the resistance of the leak $e\ f$, and R be the resistance of the voltmeter, then the total resistance by way of the ground, between the conductors, would be,

$$\{R \times r/(R+r)\}+r_1,$$

and if V=voltage of the circuit,

v=reading of voltmeter from a to c,

v_1=reading of voltmeter from g to c,

Then $r=R\{V-(v+v_1)\}/v_1$

and $r_1=R\{V-(v+v_1)\}/v$

The sum of the resistance $r+r_1$ will be

$$=R\ (v+v_1)\ \{\ V-(v+v_1)\ \}/v_1 v$$

Example 17. In a certain test, where a 220-volt generator was used as a source of E. M. F. and a voltmeter having a resistance of 20,000 ohms was used to read voltages, the indicated readings as in Figs. 7·23 to 7·26 were obtained. What was the insulation resistance to ground of each side of the circuit and what was the insulation resistance between circuits ?

Solution :—

For the resistance of conductor 1 substitute in the formula :—

$X=R(V/V_1-1)=20{,}000(220/5-1)=860{,}000$ ohms =insulation resistance of conductor 1 to ground. (Fig 7·24)

For the resistance of conductor 2 :—

$X=R(E/E_1-1)=20{,}000(220/4-1)=1{,}080{,}000$ ohms =insulation resistance of conductor 2 to ground—Fig. 7·25.

For the insulation resistance between conductors :—

$X=R(V/V_1-1)=20{,}000\ (220/2-1)=2{,}180{,}000$ ohms =insulation resistance between conductors 1 and 2 (Fig 7·26).

Example 18. Voltmeter of 15,000 ohms resistance gave the following readings.—

Between mains 220 volts.
Positive mains to earth 127 volts.
Negative mains to earth 43 volts.

(1) Find the insulation resistance to each main.
(2) If the negative main is earthed through an ammeter, what will be the reading on the instrument ?
(3) If neither main is earthed, what is the leakage current ?

Solution :—

(1) Resistance of positive main

$=1{,}500\ \{\ 220-(127+43)\ \}/43$
$=(50/43)\times 15{,}000=17{,}442$ ohms.

Resistance of negative main$=(50/127)\times 15{,}000$
$=5{,}906$ ohms, nearly.

(2) The ammeter reads the leakage current through the insulation of the positive main.

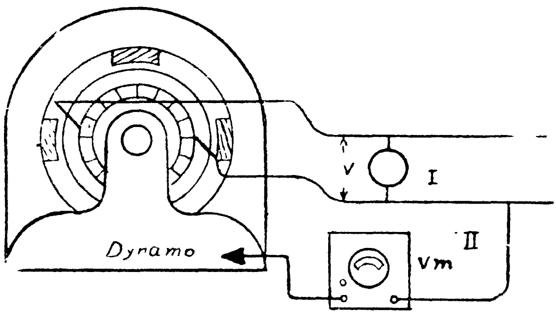
$\therefore$ earth current$=220/17{,}442=\cdot 0126$ amp.

(3) The leakage takes place through the insulation resistances of the positive and negative mains in series.

$\therefore$ The leakage current$=220/(17{,}442+5{,}906)=\cdot 0094$ amperes.

(f) **The insulation resistance of a generator** can be determined with a voltmeter of known resistance which is successively connected and read in. The external circuit connected to the generator should be cut off while the measurements are being taken so that its insulation resistance will not affect the readings

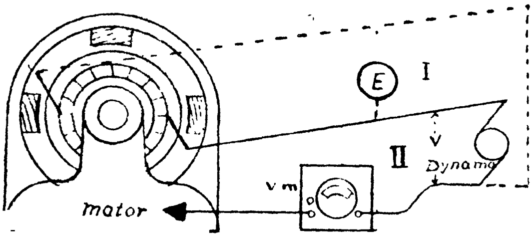
$$r=R\,(V/V_1-1).$$



Measuring Insulation Resistance of a Generator.

Fig 7·29.

(g) **The insulation resistance of a motor** can be measured with a voltmeter. If the external circuit has high insulation, the same formula for the dynamo will apply. But if it is connected to public circuits of questionable insulation, first find the circuit insulation. Fig. 7·30 shows the connections to motor for determining the insulation by current from an operating circuit.



Measuring Insulation Resistance of a Motor
Fig. 7 30.

$$r=R\ (V/V_1-1).$$

If r=total resistance of circuit and motor in multiple to ground, and r_1 is the insulation of the circuit from ground, X, the insulation of the motor will be

$$X=r_1\times r/(r_1-r).$$

(**h**) **Power** in direct-current or non-inductive alternating-current electric circuits *can be measured* with a voltmeter and an ammeter. For two-wire circuits the

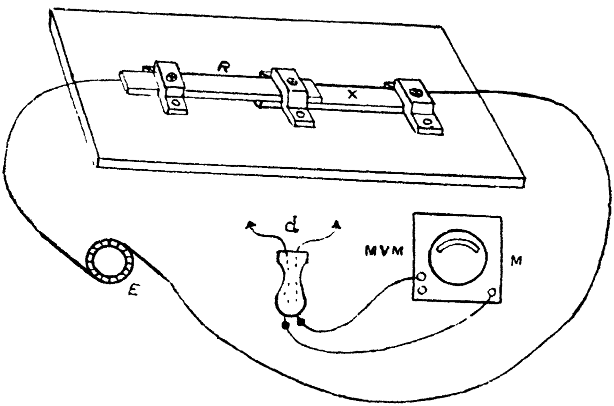


Fig. 7'31.

power in watts equals the product of volts *times* amperes, thus :—

$$P=I\times E$$

where P is the power in watts, I is the current in amperes and E is the E. M. F. in volts.

(i) Conductivity with a Millivoltmeter :—This is a quick and convenient method of roughly comparing the conductivity of metal with that of a standard piece.

In Fig 7·31, R is a standard bar of copper of 100 per cent. conductivity at 70° F.; this bar may be of convenient length for use in the clamps, but of known cross-section. X is the piece of metal of unknown conductivity, but of the same cross-section as the standard. E is a source of steady current, and if a storage battery is available, it is much the better for the purpose. M is a millivoltmeter with the contact device d. The distance apart of the two points may be anything, so long as it remains unaltered and will go between the clamps on either of the bars.

Now, with the current flowing through the two bars in series, the fall of potential between two points the same distance apart and on the same flow-line will, on either bar, be in proportion to the resistance, or in inverse proportion to the conductivity; therefore, by placing the points of d on the bars in succession, the readings of the millivoltmeter will give the ratio of the two pieces.

Example 19. If the reading for $R=250$ millivolts,
and „ „ „ $X=260$ millivolts,
then percentage conductivity of X, as compared with R, is 260 : 250 : : 100 : conductivity of X,

or, $250\times 100/260=96{\cdot}15$ %.

426. The Meggar Testing Set :—This is a very convenient portable instrument used for testing the insulation resistance. It consists of a magneto-generator D (Fig. 7·32) and an ohmmeter combined. The action depends upon the ratio of the strengths of two magnetic fields, one of which produced by a coil called the pressure coil BB' and the current coil A which are rigidly connected at a definite angle to each other but are capable of

moving as a system over an iron core on a spindle to which the pointer is fixed.

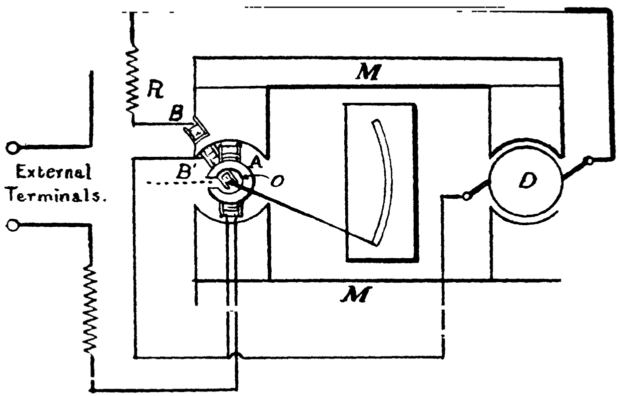


Fig. 7'32.

Flexible leads being connected to the coils, *MM* are permanent magnents which furnish the fields both for the instruments proper and the magneto-generator *D*, which gives the testing voltage. If the insulation is perfect, current only passes through the shunt or pressure coil *BB'* and sets up a magnetic field, which so acts that the pointer is at infinity on the scale. If, however, the insulation is improper, current passes through the series or current coil and as the strength of current is directly proportional to the resistance of insulation, the scale over which the pointer moves can be graduated to read directly in ohms.

It is direct-reading, simple in manipulation ; it gives result with rapidity, furnishes a large testing voltage that will search out defects of high resistance. It is rugged in construction and can be used anywhere and anyhow.

***427. Theory of the Ballistic Galvanometer :**—The deflections of the galvanometer are proportional

V. Karapetoff's Experimental Electrical Engineering.

to variations in the flux through the secondary coil. We shall prove (*a*) that electrical discharges through the galvanometer are proportional to variations in flux, and (*b*) that galvanometer deflections are proportional to electrical discharges. Hence, it will follow immediately that deflections are proportional to variation in flux.

(*a*) Electrical discharges through a ballistic galvanometer are proportional to changes in the flux. Let N be an instantaneous value of a variable magnetic flux; the instantaneous E. M. F. e, induced by a variation of this flux, in an exploring coil that surrounds it is,

$$e=s\,(dN/dt)\;10^{-8}.$$

where s is the number of turns in the coil. Let r be the total resistance of the galvanometer circuit, L its inductance. The total E. M. F. $e=L\,di/dt+ir$; the instantaneous current i in the galvanometer is determined by the relation

$$e=ir+L\,di/dt.$$

Substituting e from the above gives

$$s\,(dN/dt.)\;10^{-8}=ir+L\;di/dt.$$

$$\text{or, } s\,dN\,10^{-8}=ir\,dt+L\,di.$$

Let ϕ_1 and ϕ_2 be the initial and the final values of the flux during the short period t of the change. Integrating the preceding equation over the period t we obtain.

$$s\,(\phi_1-\phi_2)\;10^{-8}=r\int_0^t i\,dt+L(i)_0^t.$$

The integral on the right side represents the total quantity of electricity in coulombs or ampere-seconds which are discharged through the galvanometer; denoting this discharge by Q_1 the second term to the right $=0$, because the current is zero at the beginning and at the end of the discharge period. Thus we have—

$$s\,(\phi_1-\phi_2)\;10^{-8}=rQ \qquad \ldots \qquad (1)$$

This proves the above statement that an electrical discharge through the galvanometer is proportional to the variation in the flux.

(*b*) Deflections of ballistic galvanometer are proportional to brief discharges through it. After an electric discharge has passed through the moving coil of a galvanometer, the coil begins to move against the following forces :—

(1) Torsion of the suspension wire, or the springs.
(2) Currents induced in the coil and in its aluminium frame.
(3) Air resistance.

Let the final deflection be θ_1 degrees with a given discharge of Q coulombs. The force of torsion is proportional to the angle of torsion; thus the total resisting impulse of the suspension wire is proportional to.—

$$\int_o^{a_1} \theta\, dt.$$

The currents induced during the movement of the coil are proportional to instantaneous angular velocities $d\theta/dt$; their impulse is proportional to

$$\int_o^{a_1} (d\theta\,/dt.)\; dt = \theta_1. \quad \dots \quad \dots \quad (2)$$

Now, suppose a different discharge Q_2 to be sent through the galvanometer, such that the new angle of deflection $\theta_2 = 2\,\theta_1$. The time of one swing of the galvanometer is practically independent of the angle of deflection (as in the pendulum); therefore, all intermediate angles θ and angular velocities must be doubled. Thus, the impulse of the suspension wire is doubled, and that of the induced currents. Therefore, Q_2 must be $= 2\,Q_1$ in order to give a double moving impulse. This proves that electrical impulses, or discharges, and galvanometer deflections are proportional The air resistance is not exactly proportional to angular velocity, and, therefore, somewhat vitiates the result ; but its influence is usually negligible.

The same theory applies to the fluxmeter, only the time of the discharge does not influence the results. This is because the instrument possesses no resisting

torsion, and all of the electric impulse is absorbed by induced currents, according to expression (2).

(*c*) Final formula—Denoting the galvanometer constant by b, we have

$$Q = b\phi \quad \ldots \quad \ldots \quad \ldots \quad (3)$$

Where ϕ is the scale deflection. Consequently,

$$s\,(\phi_1 - \phi_2)\;10^{-8} = br\,a \quad \ldots \quad (4)$$

Let, for instance, the constant of the galvanometer be $b = 20 \times 10^{-6}$ coulombs (ampere seconds) per 1 cm. of scale deflection. Let the resistance of the galvanometer circuit, r, equal 4,000 ohms, the number of turns in the exploring coil $s = 109$. A certain flux was established through the coil, and then the exciting circuit suddenly opened, causing a galvanometer deflection = e25 cms. The final flux $\phi_2 = O_1$ and we have $\phi_1 = (10^8/100) \times 20 \times 10^{-6} \times 4000 \times 25 = 2{,}00{,}0000$ maxwells.

428. Vibration galvanometers can be used wtih alternating currents. There are two types, the core and the *soft iron magnet.* In the former, the moving element is a single wire or a narrow coil of five wires suspended between the poles of a permanent magnet. An exceedingly small mirror is attached at the centre of the wire or coil. When the natural period of this moving system coincides with that of the current to be measured, it will be set vibrating by extremely small currents, the indication being the width of the spot of light on the screen or scale. The instrument is " tuned " (adjusted to resonance) by changing the effective length of the suspension or its tension. The Einthoven galvanometer makes a very sensitive vibration instrument.

The Einthoven string galvanometer is of the moving coil type, but the coil is a single wire suspended between the poles of a powerful electro-magnet Its deflection is observed with a microscope. By using filaments of fine silvered quartz extremely high current sensitivities have been obtained.

In the soft iron magnet type, a very small piece of soft iron is suspended by a silk fibre between the poles of a permanent magnet or electro-magnet. Adjacent is a coil carrying the alternating current to be measured,

which produces a field perpendicular to that of the permanent magnet. The temporarily magnetised needle vibrates in synchronism with the period of the alternating current and with an amplitude proportional to its strength. The effective period of the moving system is adjusted to resonance by shunting more or less of the permanent field by means of a movable keeper across the limbs of the magnet or by varying the electromagnets field intensity. Obviously, these instruments can be used only for detector purposes, that is, in zero method masurements, such as inductance and capacitance with bridge-networks. They are extremely sensitive and are applicable to frequencies up to 1,000 cycles per second.

429. Drysdale-Tinsley Potentiometer:—In measuring with this instrument a vibration galvanometer is used as an A. C. deflector and is tuned to the impressed frequency. The potentiometer is first balanced with an ordinary battery and a standard cell, and the reading of the electro-dynamometer is noted. By means of the change-over switch alternating is substituted for direct current and the reading is brought to the same point and held there. The phase of the potentiometer current is then roughly adjusted, and the unknown P. D. is then balanced as nearly as possible by shifting the potentiometer slides. The balance is then improved by shifting the phase of the potentiometer current and by resetting the slides; thus by a process of double adjustment, the vibration galvanometer is brought to rest, Fig. 7·33.

As the vibration galvanometer is a tuned instrument, the frequency of the A. C. supply must be kept constant. Also the wave shape of the potentiometer current and that of the unknown P. D. must be the same, as the vibration galvanometer shows the balance for the fundamental frequency only.

Current and Power Factor Measurements:—By the use of suitable non-inductive shunts alternating currents may also be measured with this potentiometer. Also by noting the reading of the phase shifting device corresponding to a balance first of the given P. D. and then

for the given current, the phase angle between the P. D. and current can be obtained by taking the difference of the two readings.

Range of Drysdale-Tinsley Potentiometer :—This potentiometer has a range of from 0 to 1·5 volts in steps of 0·001 volt. With suitable non-inductive volt-boxes its range may be extended to 750 volts. It may also be used, in conjunction with suitable shunts, for measuring alternating currents of any value.

The *errors which creep* in the potentiometers are due to (1) leakage current and (2) thermo-E. M. F.'s. The former are mainly observed when measuring voltages above 100 volts, while the latter is noticeable in connection with the measurement of very low P. D.'s.

The *leakage error can be eliminated* by carefully insulating the galvanometer, for example by standing it up on a block of ebonite. The surface of all insulators should be free from dust and the ebonite insulators should be prevented from strong light of the sun. When the measurements are being made on circuits at earth's potential, the galvanometer is brought to earth's potential by suitable connections.

To eliminate the thermo-E. M. F.s the current can be switched off the circuit under test and the potentiometer contacts set at zero. Should any deflections be observed on the galvanometer, this may be balanced, in the usual way, by moving the slider contacts, the value of the reading so obtained being added to or subtracted from the reading obtained with the test current. The thermo-E. M. F. is also generated by rapid movement of the sliding contact, if the contacts are not of suitable metal.

430. Oscillograph :—It is essentially a galvanometer of very short period It is designed to give a deflection which will follow instantaneously the variation in an electric current or voltage. It is provided with a device whereby the operator may observe the wave shape visually or record it photographically.

This has three prominent features: (1) A polarised movement to show the direction and the magnitude of the current and pressure. (2) It has extremely high

moving parts coupled with relatively large working forces, resulting in a very short neutral period of vibration. In this the natural period of moving system is so small that the deflections will always be proportional to the instantaneous value of the current following through the coil. It has the highest possible frequency of free vibration consistent with high current to voltage sensitivity. It is applicable in the observation of potentials or currents as voltmeter or ammeter mainly when the variations are too rapid to be indicated by the more usual instruments. (3) *Critical Damping* :—The control system should show no sign of elastic fatigue or hysteresis.

The Frequency of Current or Voltage :—Natural period of vibration of system should never be more than 1/30, and 1/50 is preferable with distorted waves.

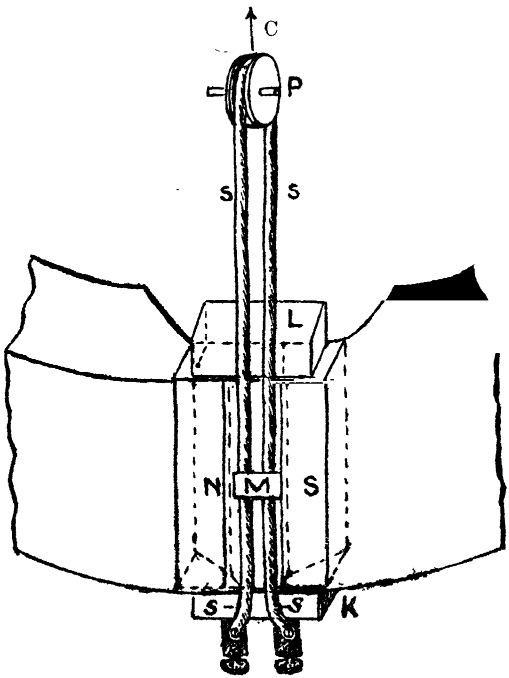
Classification :—(1) The galvanometer type.—The indicator is a beam of light from an arc lamp reflected from an extremely small mirror attached to the moving system. The path of the beam is determined visually or photographically. Recurrent or periodic waves may be rendered stationary and, therefore, visuable by suitable optical system Transient phenomena may be photographed by an instantaneous process.

(2) *Wattmeter Oscillograph* :—In this the field magnet is an electro-magnet with a winding which carries the current (through a current transformer, if necessary) of the circuit in which power is to be measured, the moving system is connected in series with a suitable resistance across the load The iron of this field magnet is worked at a low density in order to have the field intensity proportional to the current

Types :—They are of three types : (1) The moving coil ; (2) The moving iron ; (3) The hot wire.

The moving coil type of oscillogragh, which is the most common form, consists of a single turn coil formed by passing phosphor-bronze strip over a pully suspended by a spring in a narrow gap between the wedge-shaped poles of a powerful electro-magnet or permanent magnet. It is immersed in a liquid which provides critical

damping. The mirror is cemented to the strips midway between the bridges, its usual size being 0·060 inch by 0·017 inch. Tension is applied to the strips by a small spring balance. The vibrator is readily rewired in case of a break or burn out.



Oscillograph.

Fig. 7·34.

The current to be investigated passes in at *s* up *Ns* and down *Ss*. Thus one strip is urged forward and the other back, so that the mirror *M* attached to the centres is deflected through a small angle. The strips are maintained under considerable and equal

tensions by the spring *C* and in this way a controlling force is provided, the angular deflection being extremely small is practically proportional to the current following and the motion is damped by immersing the strips in a bath of oil with a glass front.

The permanent magnet oscillograph is somewhat inferior in sensibility and greatly inferior in insulation between elements compared with the electro-magnetic type of oscillograph. Again, the moving coil type has a much lower inductance than the moving iron type and, therefore, a wide range of application. On high tension circuits, without the intervention of transformers, the permanent magnet form is to be preferred, on account of the ease with which it can be insulated.

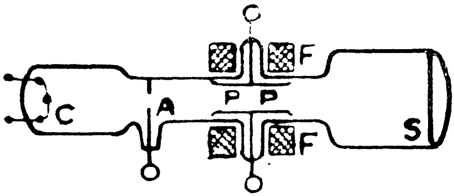
The hot-wire type is essentially a hot-wire galvanometer, giving a deflection proportional to the current flowing through it and in a direction dependent upon that of the current. Some method of overcoming sluggishness is necessary. The ratio of capacity to resistance is so adjusted as to counteract this sluggishness.

If a source of continuous current is available, the electro-magnetic pattern possesses the advantage of greater sensitiveness.

The natural period of vibration of the electro-magnet type is 1/10,000 second and of the permanent magnet pattern about 1/3,000. The sensitivity at a scale distance of 50 cms. being about 3 cms. for 0·1 ampere flowing in each case. The resistance of the strips is about 5 ohms and the current which they will carry is about 0·1 ampere ; so that for measurement of currents a shunt is employed and for pressure measurements a series resistance.

The Duddell instrument is not suitable for frequencies higher than 500 per second, under special circumstances may be employed for frequencies up to 1,000 cycles per second. The moving iron type can be used up to 1,000 cycles per secend. For higher frequencies up to 300,000 to 1,000,000 cycles per second the cathode ray tube high frequency oscillograph may be used.

431. Cathode Ray Tube Oscillograph :—The electron stream leaves a trace on a photographic filler or produces an image on a florescent screen. C is the cathode formed of a strip of platinum heated by a current from a battery A small spot of lime or of barium oxide on the centre of the strip forms the nucleus of the ray which passes across the exhausted tube at from 100 to 500 volts. After emerging through a small aperture, A, the ray passes on between a system of potential plates, PP, and field coils, F, until finally it impinges upon a divided florescent screen, S, at the end of the tube. If pressure is applied between the potential plates PP, the ray is deflected away from one end towards the other, while excitation of the coils F deflects it in the direction at right angles to this. When both are excited, the ray traces a curve on the florescent screen which indicates the relationship of pressure and current as regards both phase and magnitude As the ray possesses no inertia, the apparatus is applicable to all frequencies, but it is not at all easy to use and is only recommended for those cases in which the ordinary oscillograph is useless



High-frequency Oscillograph.

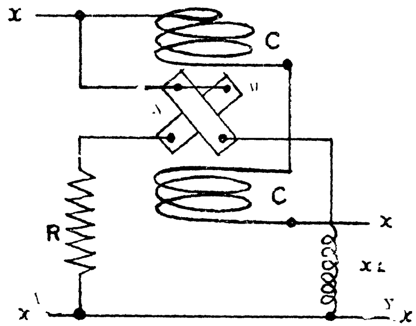
Fig. 7'35.

432. Measurement of Power Factor :—The power factor of a circuit may be measured by means of a wattmeter, an ammeter and a voltmeter, when it is obtained from the relation $W/EI = \cos\theta$. It can be, however, measured directly by the power factor meters.

There are two general classes of power factor meters—(1) those involving the principle of electro-dynamometer-wattmeter, (2) those based upon the principle of induction wattmeters.

(*i*) The arrangement is similar to that in a wattmeter except that there are two coils $M\ N$ in the moving system

(Fig. 7·36). A fixed coil *C C* carrying the main current is divided into two halves. A pair of moving coils *M N* fixed at right angles to each other is pivoted between the two portions. The coils *M N* move together and have no controlling force. *M* has a resistance *R* in series and *N* a reactance *X* in series and the two circuits are



Single-Phase Power-Factor Meter.

Fig. 7·36.

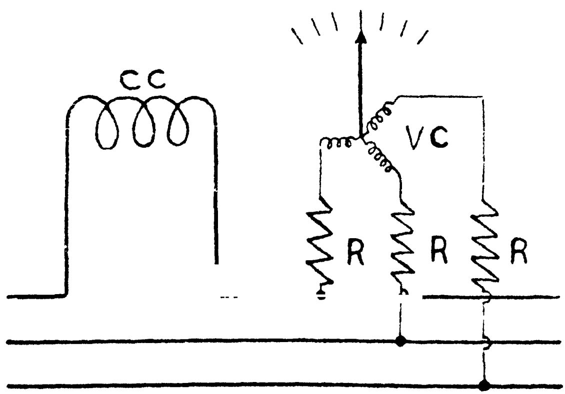
connected in parallel across the main *XY*. Hence, *M* carries a current proportional to and in phase with the voltage, but the current which passes through *N* lags behind the voltage by a large angle about 90° for the reactance

When the power factor is unity, the reaction between the fixed coils *CC* and the moving coil *M* will be a maximum and that between *C C* and *N* will be a minimum. That is, when the main current is in phase with the voltage, *M* sets itself parallel to *C C*. If the main current lags by the same amount as the current in *N*, the latter coil sets itself parallel to *CC*. For intermediate values of lag of the main current, the moving coils *MN* will take up an intermediate position such that their resultant field is in line with the field of *CC* at the instant when the latter is at its maximum value.

With leading main current the same is true, but this necessitates a movement in *MN* in the opposite directions

to that caused by a lagging current; consequently, a pointer attached to the moving coils can be used to indicate the power factor of the circuit on a scale and to show whether the main current is lagging or leading. Theoretically, the indications will be effected by frequency, but by proper design of the reactance, the effect of moderate variations in frequency can be eliminated.

(ii) Three - Phase Power - Factor Meter for Balanced Load :—In polyphase meter, the reactance is replaced by a resistance and the instrument is, therefore, entirely independent of the frequency, and the ends of the circuits of coils *MN* are connected to points between which are two P.D.s differing in phase by a fixed amount, *e.g.*, in a three-phase circuit *M* may be connected across one pair of main, and circuit *N* across a different pair. There are three coils in the moving system, one connected across each phase. The moving system takes up a position where the resultant of the three torques will be a minimum which position will vary with the average power factor of the circuit.



Weston Polyphase Power-Factor Meter for Balanced Load.

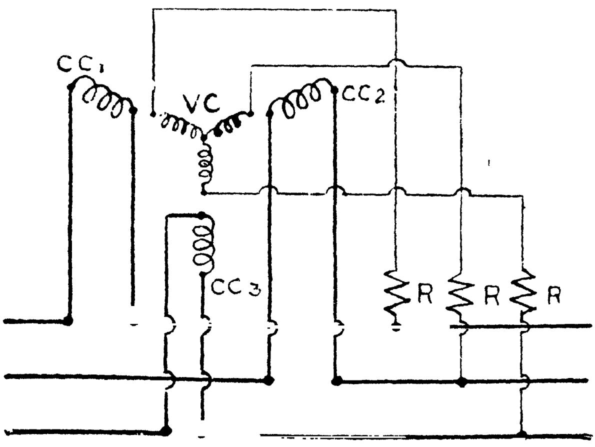
Fig. 7·37.

The main current flows through the coil $C\ C$. In the field of this is pivoted the rotor carrying the pressure coils $V\ C$ much as in a dynamometer wattmeter, except that there are three such coils spaced 120° apart. Each coil is connected through a high resistance R, to one of the mains, and, as the resistance of these three paths are made equal to one another, the common junction of the coils forms an artificial neutral point.

This instrument measures the phase angle between the current in the line including $C\ C$ and the pressure between that line and the neutral point. The readings are independent of wave form or frequency but are only strictly applicable to balanced load.

The three-line currents pass through a system of fixed coils CC_1, CC_2, CC_3 spaced 120° apart similarly to the three rotor coils VC.

(iii) **For polyphase circuits with unbalanced load** the average power factor can be found by the reading of a single instrument. This has one fixed current



Three-Phase Power-Factor Meter for Unbalanced Load.

Fig. 7·38.

coil for each phase placed at angles corresponding to the phase difference, *e.g.*, for three-phase, 3 coils at 120° apart. It has the same number of moving pressure coils and held at the same angles apart and joined to corresponding phases (usually connected for three-phase). The position taken up depends on the average power factor. By using short circuiting switches in the current coil circuits, the same instrument may be used to give the power factor of the separate phases (Fig. 7·38).

433. Reactive (Wattless) Volt-Ampere Indicators :—Operating conditions on polyphase circuits are sometimes such that the reactive component of the volt-amperes in the circuit does not vary through wide limits of load between light load and full load, whereas the power factor may vary greatly. Under such circumstances it is frequently more convenient to have a direct measure of the reactive volt-amperes rather than the power factor ; as, for example, in a railway substation employing synchronous converters. This may be secured, as noted above, by using wattmeters suitably connected to the circuit. On a balanced three-phase circuit either a single-phase wattmeter in Fig. 7·39, or a two - element ployphase meter, connected as shown in Fig. 7·40, may be used ; the instrument transformers are omitted when the voltage and current do not exceed the range of the wattmeter. The only difference between the connections shown in Fig. 7·40 and those for the two-element poly-phase wattmeter for measuring power is that the two potential circuits are inter-changed.

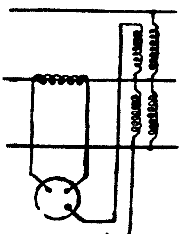


Fig. 7·39.

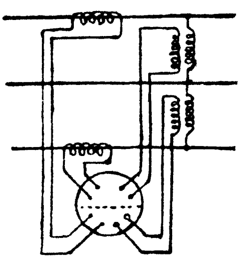


Fig. 7·40.

A wattmeter connected as in Fig. 7·39 reads $EI \sin \theta$, where E is the voltage between wires, I the line current and θ the power factor angle ; to obtain the total reactive volt-amperes of the load this reading must be multiplied by $\sqrt{3}$. A

two-element wattmeter connected as in Fig. 7'40 reads $IEI \sin \theta$, and to obtain the total reactive volt-amperes of the load, this reading must be multiplied by $\sqrt{3}/2$. This instrument in either case may be calibrated to read the volt-amperes directly.

434. Resonance Frequency Indicators:—In this instrument, Fig. 7'41, stout strips of different lengths are fastened at one end and free at the other, so that each vibrates at a particular frequency by outside impulses whose frequency is the same. The strips are arranged in the order of frequency in a circle or in lines. The strips are all acted on by magnetic impulses which are supplied by the alternating current in an electro-magnet which is connected to the circuit whose frequency is to be determined. The free period of vibration of the reed is equal to half the period of the current. The result is that each strip is attracted twice in every cycle. As the current in the electro-magnet increases, the reed is attracted towards the magnet, and as the current is reduced to zero, the reed springs away from the magnet. If the period of the alternating quantity differs but slightly from this critical value, the impulses due to the electro-magnet will not occur at favourable moments; and the strip, whose natural period of vibration corresponds with the frequency of the attractive force, has a greater amplitude of vibration than the rest which vibrates slowly or none at all, under the same

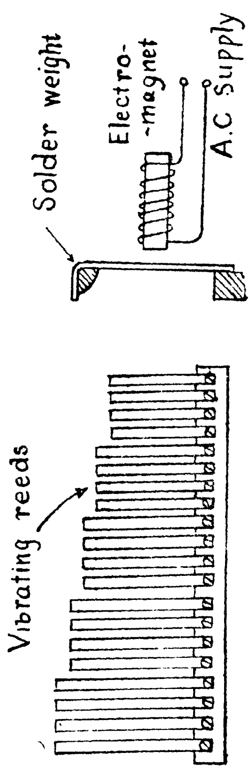


Fig. 7'41.

condition; each strip is provided at the free end with a small rectangular piece of metal, pointed white. The frequency marked in the scale opposite the one or two vibrating reeds is the frequency required.

In polarised reeds the frequency of the supply system is the frequency of the reeds thrown into vibration.

435. Campbell Frequency Meter:—In this Fig. 7·42 there is only one reed *S* whose free length is variable. One end is fastened rigidly to a sliding rack and the other free end is projected in front of an

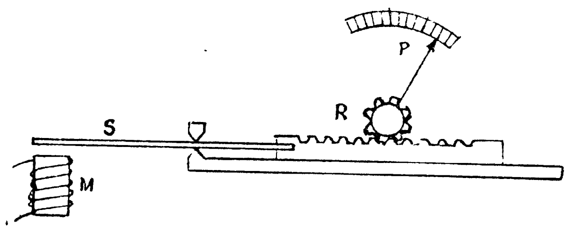
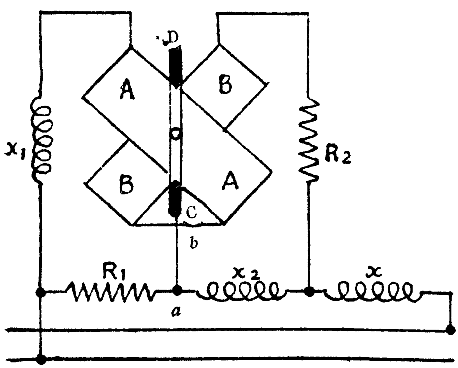


Fig. 7·42.

electro-magnet *M*. For use the rack is moved to right or to left and the maximum amplitude of vibration is noted when the corresponding frequency is indicated on a dial.



Circuits in Weston Frequency Meter.
Fig. 7·43.

436. The Weston Frequency Meter:—It works somewhat on the same principle as the movable core type of ammeter and voltmeter

with only this difference that in the latter instruments the magnetic field varies in intensity, but not in direction; whereas, in the frequency meter, the field remains constant but its direction varies with the frequency. This direction of the resulting alternating field is determined by the ratio of the currents in the two coils which are mounted at right angles to each other and is thus unaffected by a change of voltage. One of these coils AA, Fig. 7'43, is connected in series with a reactance coil X_1 and in parallel with a non-inductive resistance coil R_1 and the other is in series with a resistance coil R_2 and in parallel with reactance coil X_2, and two circuits are also connected in series.

At a particular frequency the falls of potential along X_1 and coil AA to point b is the same as that across R_1 to a, and the current through AA is the same as that through BB and in phase with it. The resultant magnetic field in this case will be parallel to CD and will remain fixed so long as the frequency remains constant

If the frequency changes, the ratio of the current in the two fixed coils also changes. Thus, any change in the frequency is accompanied by a shifting of the space position of the resultant field and this shifting causes a deflection of the pointer.

437. Functions of a Synchroscope :—It should indicate :—

(1) the difference in speed between the two generators to be synchronised,

(2) which machine is running faster and finally the time of exact synchronism,

(3) the phase difference when frequencies are equal. The principles of operation of a synchroscope are practically the same as those of power-factor meter. Thus, if the ends of the stationary coils are connected to the terminals of one alternator while the two ends of the coils wound with fine wire are connected to the generator to be synchronised, the pointer will indicate the phase difference between the electromotive forces of the two machines.

The field through the stationary coils pulsates with a frequency equal to that of the running generator, while the field on the rotating coils, due to the incoming generator, revolves. If the frequencies of both machines are the same, there is a certain position of the armature where no torque will be exerted upon it.

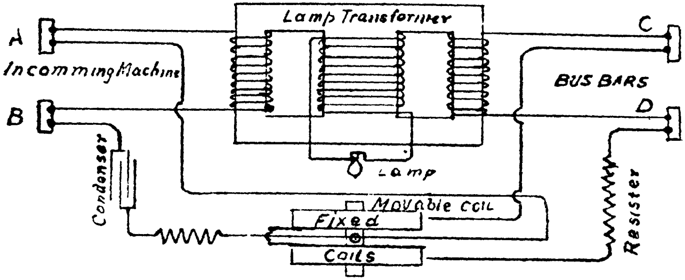
If, however, the frequencies are different, the field of one set of coils constantly changes its phase with reference to the other, and consequently there is a torque exerted upon the armature causing it to rotate. The speed of the armature is equal to the difference of the frequencies, the armature making one revolution for each complete cycle gained by one generator over the other, the direction of rotation will also depend upon the relative speeds of the two generators.

The defect is that a synchroscope working as above described would rotate in one direction if the incoming generator were too fast and in the opposite direction, if too slow.

The Weston synchroscope uses spiral springs to counteract this motion. The movement of the pointer is thus limited.

There is no iron in the instrument. The incoming machine is connected to the terminals *A* and *B*, Fig **7.44**, and the machine with which it is to be synchronised is connected to busbars at *C* and *D*. The fixed coils are connected in series with the resister and to the buses. The movable coil is connected in series with the condenser and the incoming machine. The two circuits are adjusted to exactly 90° difference in phase. At synchronism there is no torque and the movable coil is held at the zero position by the control spring. If the frequencies are the same but there is a phase difference, a torque will be exerted and the movable coil will move to a position of balance at right or left (fast or slow). If the frequencies are different, the torque will oscillate over the dial. A synchronising lamp illuminates the scale simultaneously and the direction of apparent rotation indicates the faster machine. This lamp is connected to the low voltage secondary of the transformer. The lamp is

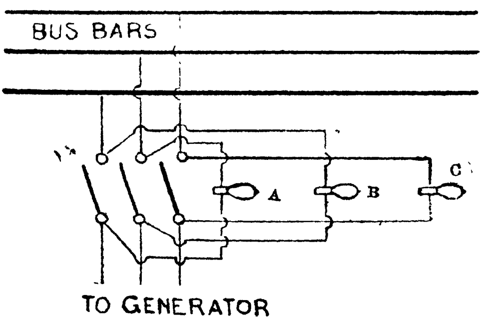
brightest when the pointer indicates exact synchronism.



Circuits in Weston Synchroniser

Fig. 7'44.

In polyphase circuits the synchronising lamps may be so arranged that they show whether the speed of the incoming generator is too high or too low. *A*, *B* and *C* are the three lamps (Fig. 7'45). *A* shows the synchronism by remaining dark; *B* and *C* are cross-connected. When the generator is exactly in phase with the busbar and the switch is open, the phase



Three-lamp Synchroniser

Fig. 7'45.

Two-phase Motors :

Minimum ammeter scale=
{Horse-power × 746/voltage × per cent. Eff. × per cent. P. F. × 2 } × (1+ per cent. O. G.).

Direct-current Motors :

Minimum ammeter scale={Horse-power × 746/voltage × per cent. Eff. } × (1 × per cent. O. G.).

Three-phase Rotary Converter :

Minimum ammeter scale=
{ kW. × 1,000/voltage × per cent. Eff. × 1·73 × per cent. P. F. } × (1+ per cent. O. G.).

Wattmeter scale=ammeter scale obtained from the above × voltage × 1·73.

Two-phase Rotary Converter :

Minimum ammeter scale=
{ kW. × 1,000/voltage × per cent. Eff. × per cent. P. F. × 2 } × (1+ per cent. O. G.).

By per cent. overload guarantee is meant the $\frac{1}{2}$, 1 or 2-hour overload guarantee on the generator and not the momentary guarantee, although some prefer to have scales calibrated to read momentary fluctuations.

The per cent. efficiency and per cent. power factor should be taken at full-load or overload.

The wattmeter scales should theoretically be multiplied by the power factor, but practically the scales work out better, as given. Integrating wattmeters have no scales and, therefore, need only have sufficient current-carrying capacity.

When the minimum scale is determined from the formula, the next larger standard scale, depending on the manufacture, should be selected.

P. F.=Power Factor. O. G.=Overload Guarantee.

Accurate reading meters should not have too large capacity, because in that case the deflection is very small under normal and light load conditions and it is not possible to take this.

Meters should not have too large capacity, because in that case the deflection is very small under normal and light-load conditions.

Exercises

(1) A moving-coil soft-iron instrument requires 350-ampere turns to produce a full-scale deflection. It is proposed to use it as a voltmeter reading up to 250 volts. Find the diameter of the copper wire with which the working coil is wound if a manganin resistance to absorb 220 volts is connected in series with it. Mean length of one turn of the coil is 118 cms.

(2) The working coil of a moving soft-iron voltmeter has resistance of 10,000 ohms at 50° C. At this temperature it was calibrated and indicated correctly 260 volts. Find the percentage error, when the temperature of the coil increases to 40° C. The coil is wound with copper wire having a temperature coefficient=0·0043.

(3) The moving coil of a voltmeter has a resistance of 200 ohms, and gives a full-scale deflection with current 0·03 amperes. Find (1) the extra resistance required for a 100-volt instrument, and (2) the error caused by a rise in temperature of 35° C., assuming the extra resistance not to change with temperature.

(4) A moving-coil voltmeter requires a current of 0·02 of an ampere to produce a full-scale deflection. What must the resistance be if it has to indicate up to 260 volts ? Also if the error caused by a rise in temperature of 20° C. has not to exceed 0·1 per cent. at maximum reading, how much of the winding must be manganin, and how much may be copper ?

(5) Calculate the dimensions of a manganin strip 0·6 millimetre thick to act as a shunt to a moving-coil instrument which gives a full-scale deflection with 0·075 of a volt across its terminals. The instrument has to measure currents up to 500 amperes. Allow a radiating surface of 12 square centimetres per watt absorbed by the shunt Specific resistance of manganin $=43\times10^{-6}$ ohms per centimetre cube.

(6) Determine the size of shunt required for a moving-coil instrument whose control is such that 4 ampere-turns produce a full-scale deflection. The instrument has to indicate up to 150 amperes. The moving

coil consists of 40 turns of copper wire having a resistance of 0·4 of an ohm, and the shunt is made of manganin.

(7) A direct-reading ammeter has a resistance of 0·04 ohm. The instrument is provided with a shunt so that the total current passing through the instrument and shunt is 10 times the ammeter reading. What is the resistance of the shunt? Would it be practicable to construct such a shunt, measure its resistance by a Wheatstone's bridge, and connect it to the ammeter terminals? If not, how could such a shunt be accurately adjusted?

(8) A direct-reading voltmeter V, having 200 ohms resistance, is connected from main 1 to earth. The voltmeter gives a reading of 3 volts and the electromotive force between the mains is 220 volts. Find the insulation resistance between main 2 and the earth on the assumption that the insulation resistance of main 1 is:—(*a*) infinite; (*b*) the same as that of main 2; (*c*) one-tenth of that of main 2.

(9) A voltmeter coil has a core $\frac{1}{2}$-inch diameter, and can be wound to a depth of 3/16 inch. It is 1·3 inch long and requires about 250 ampere-turns to produce a deflection to the full extent of the scale. What size of wire will be required to make the instrument read 150 volts total, and what will be the energy wasted in the coil if wound with copper wire covered with silk to a radial depth of 0·001 inch?

(10) An instrument is wound with copper wire, and has a resistance of 1,950 ohms at 0° C. Its dial is divided into 150 divisions, and 36·5 milli-amperes give a deflection of 80 divisions. What will be the constant of this instrument as a volt-meter at 20° C., and what resistance should the extra coil of manganin have to increase the range to 2,200 volts?

(11) A voltmeter is wound with copper, and has a resistance of 2,000 ohms at the temperature at which it was calibrated to read 150 volts total. It is first connected to the terminals of a dynamo in a hot engine-room where

its resistance rises to 2,300 ohms. It is then taken outside, where the temperature is so low as to make its resistance only 1,850 volts, and connected to the end of the circuit, but on the dynamo side of the load. The leads have a resistance of 0·02 ohms and the lamps take 100 amperes. If the true P. D. at the dynamo is 110 volts, what will the instrument read in the two cases ?

(12) An instrument reads 10 milli-amperes for 100 divisions deflection at 20° C., being wound with copper to a resistance of 100 ohms. What will it read as a voltmeter at 30° C., when a manganin extra coil of 29·00 ohms resistance is in circuit with it ?

(13) A hot-wire ammeter and a moving coil ammeter were found to give different readings on a rectified current circuit. What does each instrument measure and what would be the ratio of their readings assuming the unrectified current to be sinusoidal ?

(14) A moving-coil instrument has a resistance of 100 ohms and gives a full-scale deflection with a P. D. of 3 volts. Explain how you could use the instrument for measuring (*i*) pressures up to 120 volts, (*ii*) currents up to 20 amperes.

(15) If it is assumed that $R = E/I$, which method of connecting the voltmeter, inside or outside of the ammeter, will give the better precision when measuring a resistance of (*a*) 70,000 ohms, (*b*) 0·001 ohm ?

(16) An electrostatic and an electro-magnetic instrument (voltmeter) are used to measure the P. D. between the two direct-current mains. Compare the effects on the readings of these two instruments of putting in a resistance between the instrument and the main.

(17) An electrostatic voltmeter adapted for measuring P. D. between two mains of about 2,000 volts has one of its terminals connected with one main while the other terminal is by accident left insulated. Consider whether the voltmeter will indicate any P. D. If so, what value ?

(18) How does the construction of a quantity meter differ from that of an energy meter? Explain the principles used in different types of coulomb-meters.

(19) The reading on the dial of an energy-meter changes 13 units on passing 200 amperes at 400 volts for 10 minutes. Does the meter read fast or slow and by what percentage?

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त्वदीयं वस्तु गोविन्द तुभ्यमेव समर्पये ।

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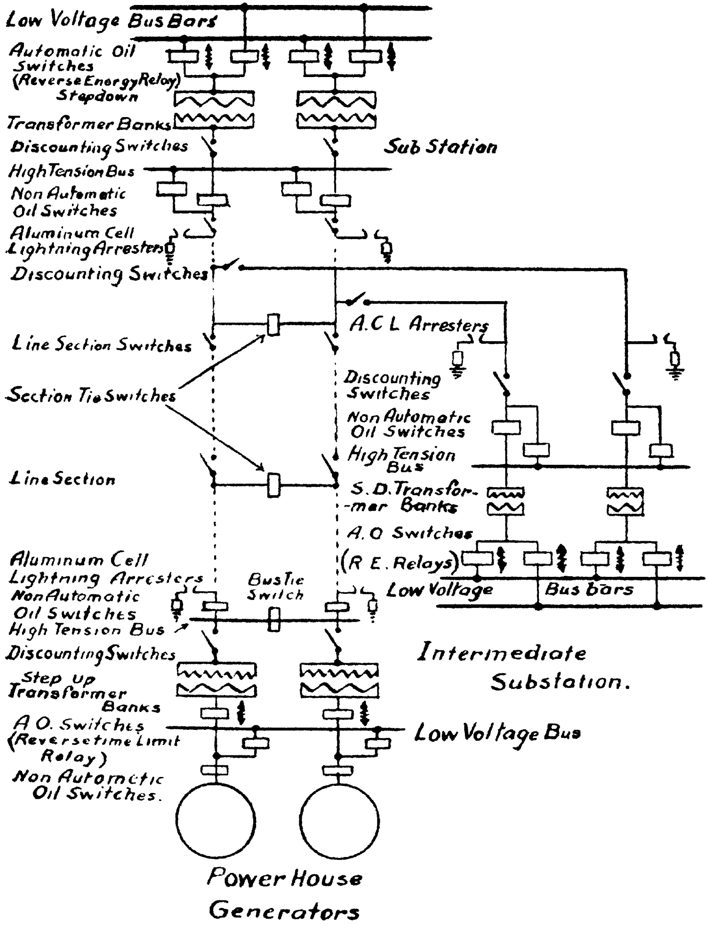
CONTENTS.

CHAPTER VIII

POWER TRANSMISSION



Power Transmission : A. C. System
Fig 8·01.

For a clear understanding of A. C. generation, transmission, and distribution system, a typical diagram has been given in the previous page, Fig. 8·01.

440. Direct Current *vs.* **Alternate Current in Power Transmission** :—Considering the line only, direct current is far superior to alternate current as its power factor is unity; it is free from the inductive disturbances and has no wattless charging current to reduce the effective output of the machines. For a given maximum voltage the quantity of wire used as conductor is much less than what is necessary in an alternating-current system. The great disadvantage is that it cannot generate a high voltage except in the Thury system. In all cases where large power is to be transmitted over a long distance, the secret of success is the use of high voltage and as such the alternate current must be used in power transmission scheme. When a comparison is made of the station apparatus of both the systems, and the entire plant, including the generating station, line, and substation, the alternate-current system is seen to be the most advantageous. It is more reliable, more flexible and, with the exemption of special cases, is probably cheaper than the direct-current system. But the disadvantages of high tension are mainly (1) higher and more costly insulation of the line and electrical appliances such as are used in generation, etc.; (2) the danger from high-voltage shock necessitating more costly precautions to avoid accidents.

In the constant-current system the receivers are in series and the voltage varies with the load. It is simple and economical since a high supply voltage may be used with the receiver at a conveniently low voltage. Its disadvantages :—(1) It cannot be used in a general distribution system for its simplicity is accompanied by its inflexibility. (2) Its high voltage makes it unsafe for interior wiring.

Use :—Suited for (1) series arc lamp due to the instability of the arc on constant-voltage system without a wasteful series resistance; (2) isolated long distance transmission lines.

441. Comparison :—In constant-voltage system loads and generators are removed from the system by opening the circuits. In constant-current system they are short-circuited. A short-circuit is dangerous in a constant-voltage system, while an open-circuit is dangerous in a constant-current system (on account of the high voltage that would then exist across the break). In the constant-voltage system, the receivers are connected in parallel across the conductors and the receiving voltages are, as nearly as practicable, alike and independent of the powers demanded.

***442. Direct-Current (Thury) System** :—Direct-current transmission is, at present, limited by the difficulty of obtaining a voltage sufficiently high for economical transmission, but Thury has developed in Europe a high-voltage, direct-current system, and a number of such plants are at present giving satisfactory service (Figs. 8·02 and 8·03) The required line voltage is obtained by connecting series-wound generators, in series the voltage per commutator ranging from 1,300 to 4,000 volts. Each generator is mounted on an insulated platform and connected to its prime mover by an insulated coupling. When not in use, the generator is short-circuited. In this system the current is maintained constant by automatic devices which control the prime-mover speed, shift the brushes, and shunt the field, and the voltage is made to vary with the load. The power is delivered to motors similar in construction to the generators. The motor speed is controlled by shifting the brushes, and simultaneously shunting the field. Line voltages approximating 70,000 volts are in use, and a transmission distance of 112 miles (Moutier-Lyons) has been reached.

In Fig. 8·02, the connections of generators and transmission lines are shown besides the generator voltmeters, the short-circuiting switches and lightning arresters. In Fig. 8·03, the motors of different capacity and voltages have been shown.

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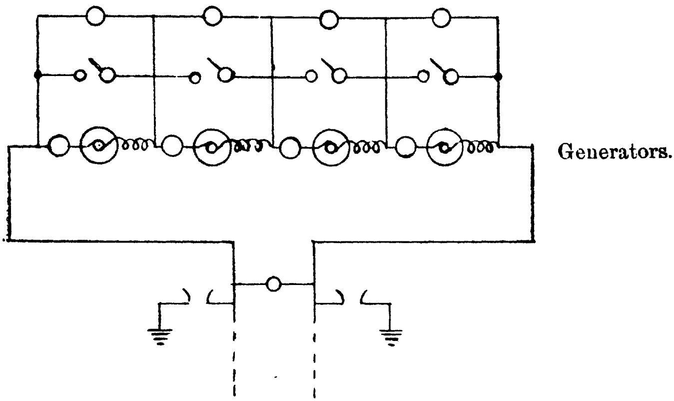
* Adapted from Standard Hand-Book for Electrical Engineers.



Typical Thury System.

Fig. 8·02.

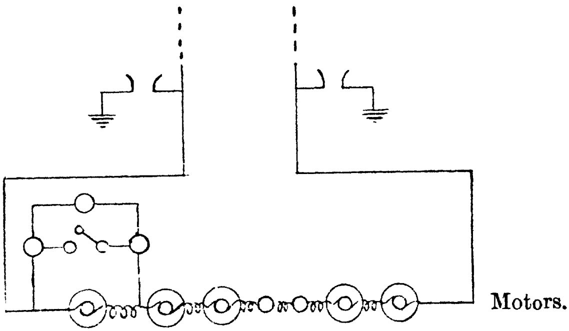


Fig. 8·03.

443. Advantages Claimed for Thury System:— (*a*) Power-factor always unity; (*b*) higher effective pressures for the same line insulation (tests by Thury indicate that with given line insulation, direct current may be twice the alternating current voltages). The maximum pressure occurs only during maximum loads;

(*c*) no dielectric losses; (*d*) two wires only to be insulated; (*e*) underground single-conductor cable can be obtained for 60,000 volts, and with grounded neutral, the line pressure would be 120,000 volts; (*f*) no inductance or capacity troubles, such as surges and abnormal voltage rises; (*g*) a number of stations can be operated in series and a station can be connected to the line at any point; (*h*) switching arrangements very simple; (*i*) in hydraulic stations under variable head, greater efficiency can be obtained since constant speed is unnecessary; (*j*) adapted for industrial work requiring constant torque; (*k*) line repairs can be easily and safely made while the line is in operation after grounding the conductor at the point in question (not applicable to systems with grounded neutral).

444. Disadvantages of Thury System:—(*a*) Insulated floors and couplings; (*b*) generating units must necessarily be of moderate capacity, though several generators may be connected to one prime mover; (*c*) the line loss is constant and independent of the load, although the current may be somewhat decreased on light loads; (*d*) constant-head water-wheel not ideal for constant current (variable speed); (*e*) special regulating devices required on motors; (*f*) impossibility of securing overload torque on the motors, even for a short period; (*g*) greater liability of damage to generators, due to lightning, and hence more expensive protective devices are required. The Transverter and the Thyratron may make possible further development in high-voltage direct-current transmission (*vide* pages 380 and 444).

445. Transmission and Distribution Circuits:—Circuits designed for transmitting relatively large quantities of power from one point to another are called *transmission lines*, while those for delivering small amounts of power at numerous points are called *distribution circuits*. Transmission lines have no or few branches, while it is the characteristic of distribution circuits to have many branches. Distribution lines are conveniently run over-head but for long distance transmission aerial lines are universal.

446. Design of Transmission Line :—In the design of transmission system the following factors must be considered :—

(*a*) *Service requirements* :—This involves the (1) consideration of voltage and frequency ; (2) amount of power transmitted ; (3) continuity of service.

(*b*) *The electrical design* :—This requires the consideration of (1) the choice of conductor ; (2) the spacing of conductors ; (3) the voltage regulation ; and (4) the line stability and corona loss.

(*c*) *System connections* :—This requires the consideration of (1) the number of parallel lines ; (2) their locations whether on the same or different routes ; (3) sectionalising switches ; (4) transformer connections ; (5) radial or ring connections of the system ; (6) number of grounds ; (7) method of grounding, etc.

(*d*) *Mechanical design* :—This involves : (1) the selection and design of the type of supports (whether steel tower, steel pole, or wood pole) ; (2) the length of standard span ; (3) location of towers or poles ; height of towers or poles, and permissible sag at various temperatures, with assumed wind and ice loads.

(*e*) *Switching* :—This involves the (1) location of both high-voltage and low-voltage switches ; (2) the methods and sequence of switching lines and transformers, whether singly or as units ; and (3) the synchronising of stations.

(*f*) *Protection* :—This involves (1) the selection and location of circuit-breakers ; (2) the selection and location of relays, whether balanced time limit or overload, etc. ; (3) the setting of these relays ; (4) the number of ground wires ; (5) the number and location of lightning arresters.

(*g*) *Transformer Substations* :—This must be located at the termination of private right of way and the power carried in the distribution centres either underground or at lower voltage. They are generally located at the centre of gravity of load, of the district they serve. The substation voltage depends on the customer's requirements and the converting apparatus available.

447. Economic design of transmission line can be made after ascertaining (1) the best location ; (2) the transmission distance ; (3) the load to be transmitted ; (4) the most economical voltage ; (5) the most economical kind and size of conductor ; its material and arrangement in the line ; (6) the most economical spans and type and length of supports ; (7) proper voltage regulation, or the choice of and selection of synchronous condensers, necessary for the best regulation.

Long span, large conductor size, large sag, wide conductor separation, very high voltages and large K. V. A. capacity lines go together in every case ; the most economical line is a compromise of a set of such conditions.

448. Transmission Line Calculation for Direct Current:—

Let—

P = power to be delivered,
E_r = the voltage at the receiving end,
I = the current,
e = the total voltage drop,
E_g = the generator voltage,
R = the line resistance,
l = the total length of conductor in feet,
η = the efficiency,
r = the resistance per circular mil foot.

Taking normal current density is 0·001 amp. per circ. mil and the drop per ft. 0·01 volt., we have—

$$E_r = \frac{E_g}{2}\left[1 \pm \sqrt{1 - \frac{4\,P\,R}{E_g}}\right] \text{ volts.} \quad \ldots \quad (1)$$

The minus sign is used if the efficiency of transmission is less than 50 %, which practically never occurs.

$$I = \frac{P}{E_r} \text{ amps.} \quad \ldots \quad \ldots \quad (2)$$

$$e = 0{\cdot}01\, l \text{ volts} \quad \ldots \quad \ldots \quad (3)$$

$$\eta = \frac{E_r}{E_r + e} \times 100 \quad \ldots \quad \ldots \quad (4)$$

Power lost per circular mil put at normal density is

$$I^2r=(10^{-3})^2\ 10=10^{-5} \text{ watts} \quad \ldots \quad (5)$$

Total power lost at normal density is

$$I^2R=10^{-5}\times \text{circular mil}\times l \text{ watts} \quad \ldots \quad (6)$$

If the current density differs, the right-hand side of equation (6) is multiplied by the square of the ratio of the densities.

Note that the high-voltage constant-current systems are designed so that the line losses are kept within prescribed limits

449. Transmission Line Calculation for A. C. :—

Let—

E_o be the voltage of the alternator,
E the voltage at the supply terminals,
E and i' are in time-phase,
E and i are in time-quadrature.

Let—

E be known and be taken at the zero vector $= e$.

$$E_o = e+IZ=e+(i+ji^1)\ (r+jx),$$
$$= e+ir+ijx+ji'r-i'x,$$
$$=e+ir-i'x+j\ (ix+i'r)=a+jb.$$

where, $a=e+ir-i'x$,
$b=ix+i'r$.

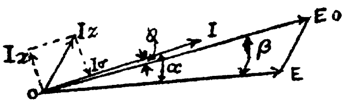


Fig. 8'04.

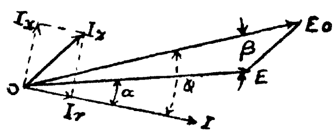


Fig. 8'05.

The power factor of the load, $\cos\alpha = \frac{ei}{eI} = \frac{i}{I}$.

Generator volt. amp. $= IE_o$,

$P_o = E_o I \cos\phi$, where ϕ is the angle between E_o and I.

For leading current—

$\phi = \alpha - \beta$; where β is the angle between E_o and I.

$\therefore \cos\phi = \cos(\alpha-\beta)=\cos\alpha\cos\beta+\sin\alpha\sin\beta.$

But $\cos \alpha = i/I$, and $\sin \alpha = i'/I$

Similarly, $\cos \beta = a/E_0$ and $\sin \beta = b/E_0$.

$\therefore \cos \phi = (1/IE_0)(ia + i'b)$.

Substituting this value into the equation for power of generator,

$P_0 = E_0 I \cos \phi = ia + i'b.$

Power factor at the generator,

$$= \frac{\text{Power}}{\text{Volt-amp.}} = \frac{P_0}{E_0 I}$$

Efficiency of transmission $= Ei/P_0$.

$$\textit{Apparent Efficiency} = \frac{\text{output}}{VA \text{ input}} = \frac{Ei}{E_0 I}$$

$$\textit{Regulation} = \frac{E_0 - E}{E}$$

450. Frequency :—The low frequency is more suitable for power transmission for the following reasons :—

(1) The inductive drop, $2\pi f LI$, is small, hence the regulation is better than for high frequencies. There are lower iron losses in the generating machines.

(2) The capacity current, $2\pi f CE$, also increases with frequency. It results in reducing the energy output of the generators and transformers. There is less charging current taken by the line.

(3) The problem of operating generators and other synchronous apparatus is less difficult in the case of low frequency.

Frequency of Generators :—Induced E. M. F. is directly proportional to frequency. The cost is slightly increased if the frequency is decreased. With an increase of magnitude and range of service a lower frequency improves the operation of alternators in parallel and the line regulation is also benefited.

(4) The power factor of the induction motor decreases as the frequency is raised.

The 25-cycle motor has an inherently lower reactance and requires less magnetising current for a given speed, for which reason its power factor is higher than for high-frequency motors.

The starting torque and the maximum torque depend inversely on a function of reactance, and are higher for low frequencies.

In fact the efficiency of an induction motor depends upon a number of factors. The lower frequency will, of course, tend to make the iron loss less, but, on the other hand, the copper loss will be considerably greater on account of the longer end-connections, and, as a rule, the efficiency is found to be somewhat lower for low than for high frequency motors.

(5) Electrical oscillations are less liable to be set up at low frequency.

(6) The output of a transformer may be shown to vary as the three-eighth power of the frequency.

The frequency has a very important effect bearing both on the *design and operation of transformers.* With transformers and other electrical apparatus using two windings and an iron core, the ratio of turns, the factors remaining the same, will vary approximately inversely as the square root of the frequency. The lower the frequency, the larger the flux, and the larger the number of turns for the same voltage. Therefore, transformers increase in the cost and weight as the frequency decreases.

The regulation of 25-cycle transformer is not quite as good as for 60-cycle, on account of the increased drop, due to the greater number of turns and their increased mean length ; and the efficiency is also slightly less.

Operating 25-cycle transformers on a 60-cycle circuit decreases the flux density and the core loss. Operating a 60-cycle transformer on a 25-cycle circuit increases the density and core loss, and, in general, gives a prohibitive exciting current.

Frequency also affects the *mechanical forces* to which a transformer may be subjected, as the reactance increases

with the frequency, and, while the mechanical force varies directly as the square of the current, a 25-cycle transformer operating on a 60-cycle circuit would be subject to about one-half the mechanical strains on short-circuit. The reactance of power transformers generally ranges from 6 to 10 per cent.

(7) Commutation troubles arise in the synchronous converters at high frequencies.

A synchronous converter being in effect a combination in one machine of a synchronous motor and a direct-current generator, the important factors in which the frequency is concerned have to do almost entirely with the continuous-current side. The continuous-current generator, as a rule, runs at frequencies much below 25 cycles, and the frequencies of synchronous converters, especially for 60 cycles and above, the problems of commutation and commutator construction become of importance.

Improved types of synchronous converters, operating at 60 cycles, are in market. They operate satisfactorily and efficiencies of lower and higher frequency types are practically the same.

The standard frequency for transmission purposes should be adopted, namely, 25 or 50; the American practice is 60.

451. Frequency and Illumination:—25-cycle energy, however, cannot be used for arc lighting, and is not satisfactory for incandescent lighting, except out of doors, owing to the noticeable flickering of the light. Glow lamps may be run without flickering from a supply of 22 cycle but below this they will show a slight flickering.

452. Considerations Which Determine the Size of Conductors:—The required size of conductors is determined by—

(*a*) *Mechanical Strength:*—This is of primary consideration in any transmission line. Hard-drawn copper wire has a breaking stress of from 25 tons per square inch in large sizes to 29 tons in smaller sizes used for overhead line.

The smallest wire permissible under Indian Elec. Rules (No. 57) must have a breaking stress of 800 lbs, which is equivalent to No. 10 S. W. G. for a span not exceeding 220 ft. In practice, it is seldom advisable to use a smaller wire than No 6 S. W. G.

(*b*) *Permissible Energy Loss* :—This is determined by factors such as the cost of generation, selling price, load factor, and either the economic drop or Kelvin's Law.

(*c*) *Required Voltage Regulation* :—It is not difficult to secure, as automatic regulators and synchronous apparatus may take care of any voltage fluctuations at the substations. If, however, the inductive line drop for a given cross-section of conductor is too great, two separate lines of half the cross-section may be used.

(*d*) *Corona.*

(*e*) *Cost* :—Such as the relative cost of line, of plant and of line maintenance may determine the size of conductors. The larger the line conductor, the smaller will be the energy loss, but the fixed charges for the line will be increased. The conductors may be so chosen that the sum of these last two quantities is a minimum.

(*f*) *Current-carrying Capacity of the Conductors* :—This is usually ample when the size of the wire is determined by the permissible energy loss.

(*g*) *The maximum permissible temperature rise* :—The current-carrying capacity of a conductor, according to the Standardising Committee of the Institution of Electrical Engineers, is determined by—

$$I = 2{\cdot}6a^{0{\cdot}82}$$

where I=the current and a=the area of cross-section of the conductor in square inches. The current density is taken to be such that the maximum temperature rise

will not exceed 17° C. The conductors of smaller sectional area will be worked at a relatively higher current density than those of larger sectional area.

The area and weight of conductor in a transmission system depends upon (1) power to be supplied, (2) distance of transmission, (3) line voltage, (4) power factor of load, (5) permissible loss in transmission—ohmic drop or power loss.

453. Voltage:—The selection of high or low pressure system depends upon (1) the area and character of the district to be supplied from one central station; (2) the position of the generating station relating to the area of supply; (3) the nature and cost of the power available for driving the generators. Besides the above, capital outlay on the mains and cost of maintenance, flexibility and capability of subsequent extension and development, regulation, uniformity, reliability of pressure, and the probable dissipation of energy, leakage, and losses due to resistance, hysteresis, etc., form important points of consideration.

The voltage of a so-called constant potential system depends on (1) the length of the system, (2) the kind of apparatus, and (3) the danger to life or apparatus.

In many respects the cost of mains is the most important point. When considered as an investment, it is obvious that the interest thereon forms a very considerable portion of the fixed annual charges against the system. The first cost increases—other things being equal—with the distance over which the power, P, has to be transmitted, but not directly, and it also depends largely upon the voltage employed.

The best voltage to use on any given system can generally be arrived at by a system of trial and error taking into account the costs of the various parts of the complete system as influenced by alterations in the transmission voltage.

The determination of the most economical transmission voltage involves a knowledge of the cost and efficiency of generating and transforming machinery and controlling gear.

It is customary to allow 1,000 volts per mile of transmission line but this may be modified somewhat by considerations of line cost.

It is based upon the fact that at this voltage with copper conductors, a current density of one ampere per 1,000 circular mils gives a loss of about 10 per cent. Except for special cases, a standard voltage should be selected for new installations, to get machinery and apparatus already developed for these voltages as far as possible. In the case of large cities to transmit 5,000 to 10,000 kW., or more, this rule gives voltages which are too low for the most economical investment in cable. But if the distribution is over wide areas and the load densities very light, voltages less than 1,000 per mile is sometimes possible.

An emperical formula (Prof. Still) is :—

$$\text{Pressure in kilovolts} = 5{\cdot}5\sqrt{L}.$$

where $L =$ distance in transmission (in miles)

$$+\frac{\text{horse-power transmitted}}{200}$$

Voltages for transmission standardised by practice are 2,200 to 2,400 ; 6,000 to 6,900 ; 11,000 ; 13,200 to 13,800 ; 22,000 to 24,000 ; 33,000 ; 44,000 ; 66,000 ; 88,000 ; 1,10,000 ; 1,40,000 to 1,50,000 ; 2,20,000.

454. Influence of Voltage and Power Factor on Amount of Conductor Material.—

Let E=voltage to neutral of an n phase system of transmission,

I=the current lagging behind the voltage,

ϕ=the angle of lag on each phase of the system,

P=the total power transmitted,

R=the resistance of each line conductor,

A=the cross-sectional area of conductor,

ρ=the length of the line,

l=the resistivity of copper,

p=power loss.

Then, $P=\dfrac{EI\cos\phi}{1{,}000}$ kW. per phase ... ... (1)

$$p=\frac{I^2R}{1,000} \text{ kW. per phase} \quad \dots \quad \dots \quad (2)$$

$$=\frac{1,000\ P^2R}{E^2\ cos^2\ \phi}$$

Substituting for R, where $R=\frac{\rho l}{A}$

$$p=\frac{1,000\ P^2 l\rho}{AE^2\ cos^2\phi}$$

Hence, $A=\frac{1,000\ P^2 l\rho}{pE^2 cos^2\phi}$

Hence, the volume of copper in each line is

$$lA=\left(\frac{1,000\ p^2l^2\rho}{p}\right)\frac{1}{E^2\ cos^2\phi}$$

The quantity within bracket is a constant for any given line-transmission efficiency and given amount of power to be delivred.

455. Practical limit of line voltage is reached by (1) the increased cost of insulating the conductor, (2) the increased cost of transformers, switchgear and other terminal apparatus, with higher voltages.

456. Cause and Effect of Excessive Pressure:—The following may cause an abnormally high pressure in the whole or a part of an electric circuit :—

(*i*) Direct flash of lightning, or electrostatic induction from charged clouds.

(*ii*) Sudden interruption of highly inductive part of the circuit.

(*iii*) Sudden direct application of the normal voltage.

(*iv*) Resonance.

(*v*) The peculiar and unstable characteristics of arcs and sparks, particularly "arcing grounds."

Whatever the cause may be, the possible effects of abnormal pressure are breakdown of insulation and consequent danger to life and material. To protect the

circuit from such serious effects, devices based upon the following facts are effectively utilised in practice :—

(*a*) All carefully-designed circuits and apparatus are always provided with proper insulation so as to withstand a much higher pressure than the normal. In the case of extra high voltage systems the insulation is particularly made strong enough to withstand indefinitely many of the pressure surges occurring in service.

(*b*) Since a definite and considerable amount of energy is expended in breaking down insulation, if provision be made for removing the abnormal pressure quickly, the insulation will remain uninjured ; though, however, it may be broken down if the pressure be allowed to act for a longer period.

(*c*) An abnormal voltage has generally a very high frequency of oscillation. As a result, therefore, the current takes a path of high ohmic resistance (*e.g.*, an air gap) in preference to the normal circuit which offers enormous impedance to the high frequency current.

The causes of excessive pressure must always be avoided ; where this is impracticable, the circuit must be safeguarded by providing an easy and suitable path of discharge for the abnormal voltage, or by reinforcing the insulation of the circuit at the danger points, or by a combination of these methods.

457. (I) Economic Drop :—This determines the cross-section of the conductor. For a given voltage at the generating station, the economic drop and cross-section of a conductor for a single-phase circuit with unity load factor may be determined as follows :—

Let E = voltage at generating station,
P = power in kilowatts at generating station,
L = length of line in miles (*i.e.*, length of a single conductor),
R = total resistance of line in ohms,
X = loss in terms of impressed quantities,

A = section of conductor in circular mils,
C_1 = cost of energy in rupees per kilowatt-year at generating station,
C_2 = cost of conductor in rupees per pound,
p = rate of interest and depreciation on the cost of line conductors,
r = resistance in ohms per mile of conductor having one circular mil cross-section, and
w = weight in pounds per mile of conductor having one circular mil cross-section.

The line loss $= PX$

Annual cost of line loss $= C_1\ PX$.

Weight of line conductors $= 2w\ L\ A$.

Cost of line conductors $= 2\ C_2\ w\ L\ A$.

Annual cost of line conductors $= 2\ p\ C_2\ w\ L\ A$.

$$\text{Line resistance} = R = r\frac{2L}{A}.$$

$$\text{Line drop} = EX = \frac{1{,}000\ P}{E}\ R = \frac{2{,}000\ P\ r\ L}{E\ A}.$$

$$\text{Section of conductor} = A = \frac{1{,}000\ P}{E^2}\ r\ \frac{2L}{X}.$$

The total annual charge due to line loss plus interest on conductors is—

$$C_1\ P\ X + 2\ p\ C_2\ w\ L\ A,$$

and per delivered kilowatt is

$$Q = \frac{C_1\ P\ X + 2\ p\ C_2 w\ L\ A.}{P - P\ X}.$$

Substituting the value of A, this becomes

$$Q = \frac{C_1\ P\ X + 2\ p\ C_2\ w\ L\ \dfrac{1{,}000\ P}{E^2}\ r\ \dfrac{2\ L}{X}}{P\ (1 - X)}$$

$$\text{or, } Q = \frac{C_1\ X}{1 - X} + \frac{p\ C_2\ r\ w\ 4\ L^2\ 1{,}000}{E^2\ X\ (1 - X)}$$

If K is substituted for $p\ C_2\ r\ w\ 4\ L^2\ 1{,}000$, then

$$Q=\frac{C_1\ X}{1-X}+\frac{K}{E^2\ X\ (1-X)}$$

To find the minimum value of Q, its derivative is placed equal to zero, and we have

$$\frac{d\ Q}{d\ x}=C_1\ X^2+\frac{2\ K}{E^2}X-\frac{K}{E^2}=0.$$

$$\therefore X=-\frac{K}{E^2\ C_1}\pm\left[\left(\frac{K}{E^2\ C_1}\right)^2+\left(\frac{K}{E^2\ C_1}\right)\right]^{\frac{1}{2}}.$$

But as X is positive—

$$X=\frac{-K}{E^2\ C_1}+\frac{1}{E^2\ C_1}\sqrt{K^2+E^2\ C_1\ K}$$

If the above is worked out for a constant or fixed delivered E. M. F. instead of a fixed impressed E. M. F. allowing the latter to become what it might, the expression for Q would be the same except that the denominator would be P instead of $P\ (1-X)$, the quantities E, X and P, etc., being then delivered quantities instead of impressed quantities. If this be done, and the value of Q be differentiated, we get

$$\frac{dQ}{dX}=C_1-\frac{K}{E^2X^2}=0$$

Hence, $\dfrac{K}{E^2X}=C_1X$, that is the well-known relation,

interest = loss.

A three-phase line requires three quarters as much conductor material as a single-phase line transmitting the same amount of power with the same loss. Each conductor of a three-phase transmission line has one-half the area of each conductor of the equivalent single-phase line.

To find the economic drop of a three-phase line multiply $2pC_2wLA$ by 3/4. Then $\frac{3}{4}K$ will be substituded for K. Solving for the economic drop,

$$X = -\frac{3}{4} \cdot \frac{K}{E^2 C_1} + \frac{1}{4 E^2 C_1} \sqrt{9K^2 + 12E^2 C_1 K.}$$

The area of each conductor is

$$A = \tfrac{1}{2}\left(\frac{1{,}000P}{E^2}\, r\, \frac{2L}{X}\right)$$

Example 1. A 1.000 kilowatt is to be transmitted a distance of 6 miles over a three-phase circuit using copper conductors, with a voltage of 6,600 at the generating station ; the frequency is 50. Determine the economic drop.

Solution :—

r for one mil foot of copper=10·4 ohms,*

∴ for one mile=55,000 ohms.

(Note that r for aluminium=17 ohms, ∴ for one mile of aluminium wire r=85,000 ohms).

W=0·01484 pound of copper, (0·0048 pound for aluminium).

Assume

C_1=Rs. 50/-

(1 kW. is supplied to customers in Calcutta, Bombay and Madras for Rs. 8/- per month).

Note that C_1 depends upen a number of factors, *e.g.*, class of undertaking, capacity of plant, nature of prime mover, sale of units per annum, load factor, fuel, oil, waste, stores, etc., wages, repairs and maintenance, rent, rates, taxes, management, salaries, office expenses, legal expenses, insurance, etc.

* Note that one mil foot of soft copper has a resistance of 9·38 international ohms, and for hard copper 9·59 at 0° C and area in square mils = $\frac{\pi}{4}$ area in circular mils.

$C_2 = 0{\cdot}75$ (rupee).
$p = 0{\cdot}045$ (rupee).
$K = p\, C_2\, r\, W 4 L^2 .\ 1{,}000$
$= 4 \times {\cdot}045 \times {\cdot}75 \times 55{,}000 \times {\cdot}01484 \times 1{,}000 \times 36$
$= 3{,}966{,}732$

Hence, $X = -\frac{3}{4} \times \frac{39{,}66{,}732}{(6{,}600)^2 \times 50} +$

$$\left[\frac{\{9 \times (3{,}966{,}732)^2 + 12(6{,}600)^2 \times 50 \times 3{,}966{,}732\}^{\frac{1}{2}}}{4 \times (6{,}600)^2 \times 50}\right]$$

$= {\cdot}051$,

or the economic drop is 5·1 per cent.

$$A = \frac{1}{2}\left[\frac{1{,}000 \times 1{,}000}{(6{,}600)^2} \times \frac{2 \times 6}{X} \times 55{,}000\right]$$

$= 145{,}000$ circular mils,
take 4/0 S.W.G.

(II) Economic Voltage Drop :—Alternative Method—

(*a*) Annual charges depending upon the cost of conductor :—

Let C_2 = cost of conductor in rupees per pound weight.

P = percentage to be taken to cover the annual interest and depreciation.

R = resistance in ohms per mile of conductor.

Annual charge $= C_2 \times P \times K/R$ ... ... (*a*)
where K is constant depending upon the material of the conductor.

(*b*) Annual cost of energy lost :—

Let p_1 = the cost per H.P. year of the wasted energy ; then, annual cost per mile of conductor $= p_1 \times$ H. P. lost per mile,

$= p_1 \times I^2 R/746$
$= p_1 X^2/746 \times R$ ... ... (*b*)

where X stands for ohmic drop in volts per mile of conductor.

In order to fulfil the conditions laid down by Kelvin's Law, the values derived in (*a*) and (*b*) must be equal.

$\therefore\ C_2 \times P \times K/R = p_1 \times X^2/746 \times R$

$\therefore\ X^2 = 746 \times K \times C_2 \times P/p_1$

If the material of the line is copper, the constant K may be taken as 8·76, while for aluminium it is 4·32.

$$\text{Substituting, } X = 81\sqrt{\frac{C_2 \times P}{p_1}} \text{ for copper}$$

$$= 56{\cdot}6\sqrt{\frac{C_2 \times P}{p_1}} \text{ for aluminium.}$$

458. Kelvin's Rule:—The economic balances between loss of power and the cost of copper in the distribution of electric current, are, to a large extent, opposed to each other.

The first cost of erection of a transmission or distribution line consists of two almost independent items.

(1) The cost of the copper.

(2) The cost of poles, cross-arms, pins, and insulators and the cost of erection.

The most economical size of wire is that which makes the annual cost of energy wasted in transmission equal to the annual cost of interest and depreciation on the capital cost of the conductor used in the cable.

The economic balance between loss of power and cost of copper always leads to a definite sectional area of the conductor per ampere of current, without regard to the voltage or to the distance of transmission.

Let h = hours of supply of electric power each year.

p = cost of generating energy in rupees per kilowatt hour.

c = cost of copper in rupees per pound.

t = interest charge on invested capital (including a small percentage to cover the depreciation of copper wires and taxes) per annum.

Still's Overhead Electric Power Transmission.

l = length of the line ; hence, $2l$ the length of the wire in feet.

A = sectional area in circular mils.

R = resistance in ohms of $2l$ feet of wire.

W = the weight in pounds of $2l$ feet of wire.

I = current in amperes R. M. S.

Taking resistance of one foot of copper = 10·8 ohms.

$R = 10{\cdot}8 \times 2l/A$

$\therefore$ the power lost $= (21{\cdot}6l/1{,}000 \times A)\ I^2$ kilowatts.

The annual loss of energy $= (21{\cdot}6l/1{,}000 \times A) \times I^2h$ kilowatt-hours.

The cost of the energy lost at p rupees per kilowatt-hr. $= (21{\cdot}6l/1{,}000A) \times I^2 \times ph$ rupees per year.

On the other hand $W = 0{\cdot}00000303 \times 2l \times A$ pounds

The cost of $W = 0{\cdot}00000606 \times lAC$ rupees.

The interest on this cost is $0{\cdot}0000000606 \times l\ A\ c\ t$ rupees per year.

The total cost for loss of energy and interest on the cost of copper is

$(21{\cdot}6l/1{,}000 \times A)\ I^2ph + 0{\cdot}0000000\ l\ A\ c\ t.$

We have to choose the value of A such that this total cost is the minimum, which condition is secured by differentiating the expression with respect to A and placing the differential coefficient equal to zero.

Hence, we get $-\ (21{\cdot}6l/1{,}000\ A)\ I^2\ ph + 0{\cdot}0000000606\ l\ c\ t = o$ from which l cancels out

$$\frac{A}{I} = \text{circular mils per ampere.}$$

$$= 597\sqrt{ph/ct}$$

$$\therefore A = 597\ I\sqrt{ph/ct}$$

When the delivery current is not constant, the square root of the average value of the square should be used.

When insulated cables are used, the cost of insulation must be considered. This increases with the size of the cable though not proportionately to the area. The cost can be represented by the equttion.

$c = Ap + d$, where p and d are constants.

The minimum total cost in such cases will be obtained by making the annual cost of the energy lost equal to the annual cost comprising of interest and depreciation on that part of the capital cost of the cables which varies as the area.

Kelvin's law is only approximate and difficult to apply. The conditions which are necessary for the correct application of Kelvin's law are not usually met with in practice. The cost of conductors is seldom proportional to the amount of copper owing to the existence of such items as cost of manufacture, installation and insulation.

Example 2. Find the most economical size of cable to use, for transmitting 1,000 kilowatts 6 miles for 10 hours per day with 300 working days in the year. P. D. at the receiving end 6,300 volts.

Cost of concentric cable for this pressure

$$= \text{Rs. } (40\,A + 4{\cdot}8) \text{ per yard}$$

where A = cross-sectional area in sq. in.

Cost of generation = 1/16 of a rupee per B. O. T. unit.

Interest and depreciation together 10 per cent. per annum. Take resistance of a single-core cable at the working temperature as $\cdot046/A$ ohms per mile.

Solution.—

Interest and depreciation of cable per year =

$$\text{Rs. } (10/100) \times (40\,A + 4{\cdot}8) \times 1{,}760 \times 6$$

$$= \text{Rs. } 1{,}056\,(40\,A + 4{\cdot}8)$$

Current $= 1{,}000 \times 1{,}000/6{,}300 = 158{\cdot}7$ amps.

Watts lost in transmission $= 2 \times (158{\cdot}7)^2 \times 6 \times \cdot046/A$

$$= 14{,}013/A$$

Annual cost of lost energy $= (14{,}013/A) \times (10 \times 300/1{,}000) \times 1/16 \text{ Rs.} = 2{,}627{\cdot}5/A$

$\therefore$ for least total cost $42{,}240\,A = 2{,}627{\cdot}5/A$

$\therefore A = \sqrt{2{,}627{\cdot}5/42{,}240} = \cdot25$ sq. in.

i.e., the cable should be $\cdot25$ sq. in cross-section.

With this size the current density is $158{\cdot}7/\cdot25$ $= 635$ amps. per sq. in., which will not cause overheating with this size of cable.

The annual cost of lost energy = Rs. 2,627·5/·25 = Rs. 10,510.

Annual cost of cable = 1,056 (40 × ·25 + 4·8) = 1,056 × 14·8 = Rs. 15,629.

Total = Rs. 26,139.

By applying the formula the area is

$$A = 597 \times 158{\cdot}7 \sqrt{\frac{(1/16 \times 10 \times 300}{{\cdot}75 \times 10 \times 16}}$$

= 473,700 circular mils.

The difference is due to the difference of price of the conductor and the cable.

Example 3. Show the dependance of total weight W of copper on E, the voltage of delivery, and l, distance of delivery point, or customer from station :—

Solution :—

$I = P/E \; \therefore A = (597 \; P/E) \sqrt{ph/ct}$

Substitute the value of A in the formula,

$W = 0{\cdot}00000303 \times 2 \, l \, A$

$\therefore W = (0{\cdot}003618 \; Pl/E) \sqrt{ph/ct}$

which proves the proposition.

Limitations of Kelvin's Law :—It assumes that (1) the cost of poles, cross-arms and pins, and the cost of erection of the line are the same whatever the size of the wire may be. This is approximately true for wires of moderate weight. In the case of many wires the supporting structure must be very strong and expensive in which case the law is to be modified.

(2) The cost of wire per pound is definite. This is approximately true for bare wire only. Note the difference in the case of cable.

459. Overhead *vs.* Underground Lines :—

Overhead Lines :—(1) Unavoidable for extremely high pressures transmission of power over long distances, where adequate insulation for the conductors can be provided.

(2) For low pressures when the line goes through open country. Here underground cable may be technically suitable.

Disadvantages :—It is dangerous to human life, unsightly in appearance, causes inconvenience of pole lines running down the main thoroughfares.

Underground Lines :—In the neighbourhood of cities these are used (1) to eliminate danger to human life and (2) to avoid unsightly appearance of poles and overhead conductors ; (3) they are free from way troubles as the cable follows the road ways ; (4) assure security of supply, (5) used in feedes or short lines not tapped enroute.

Disadvantage :—Very high first cost, difficult and costly to repair ; the above considerations often result in the installation of underground lines in popular districts.

Insulated cables are placed underground over distances up to as much as 10 miles, the voltages employed being from 6,000 to 13,000. For distances greater than these, higher voltages are desirable to economise in copper. With the improvement of the cable manufacture underground transmission at 130,000 volts using single-core cable is being tried.

It should be carefully noted that transmission of even moderate quantities of power by *overhead lines* over quite short distances for low-tension, three-phase system at an average power factor is rendered commercially impracticable on account of pressure drop due to self-induction. In such cases underground cables are used with advantage.

Example 4 :—

It is required to transmit 200 Electrical Horse Power,
1/2 mile distance,
400 volts pressure at the motor,
40 volts drop,
·8 power factor,
50 periods per second frequency.

Solution :—

The current will be $I = \dfrac{200 \times 746}{400 \times \sqrt{3} \times \cdot 8} = 270$ amps.

The pressure drop allowed being 40 volts, the resistance of each conductor must be,

$R = \dfrac{40}{270 \times \sqrt{3}} = 0{\cdot}086$ or $\cdot 086 \div 0{\cdot}5 = \cdot 172$ ohm per mile.

A 37/13 three-core cable has an ohmic resistance of 0·179 per conductor per mile and so would be the nearest suitable size. But if an overhead line were used with 2 feet spacing between the wires, the effective resistance $= \sqrt{R^2 + (2\pi f)^2 \times L^2} = 0{\cdot}461$ ohm.

$$\begin{aligned}
\text{where } L &= (80{\cdot}5 + 741 \log_{10} d/r) \times 10^{-6} \\
&= (80{\cdot}5 + 741 \log_{10} 24/{\cdot}322)\ 10^{-6} \\
&= (80{\cdot}5 + 1{,}387{\cdot}9)\ 10^{-6} \\
&= 0{\cdot}001468
\end{aligned}$$

$$\therefore \text{ Effective resistance} = \sqrt{(0{\cdot}179)^2 + (0{\cdot}461)^2} = 0{\cdot}494 \text{ ohm.}$$

and the pressure drop

$$= 270 \times 0{\cdot}494 \times \sqrt{3} \times 0{\cdot}5$$
$$= 115{\cdot}5 \text{ volts nearly,}$$

which shows that to keep the drop within the permissible figure of 40 volts, wires of very heavy sectional area are to be used which cannot be economical.

Note that while the inductive drop is much greater in overhead lines than in cables, the charging current is much greater in cables than in overhead lines.

460. General Formula for Determining the Sectional Area of Conductor :—

If kW. = kilowatts delivered at the end of line,
l = route in yards in length of line, not lead and return,
E_r = voltage at the point of use,
P = percentage loss of E_r,
C = a constant as follows :—

(*i*) In continuous current or single-phase 2-wire system $C = 4{\cdot}9$, say, 5.

(*ii*) In continuous current or single-phase 3-wire, outer conductors, pressure being given across outers, $C = 4{\cdot}9$, say, 5. The neutral or middle wire used in practice=0·625.

N. B.—The neutral is generally taken as half the size of the outers, in three-phase star.

(*iii*) In continuous current or single-phase 3-wire, volts being given between outer and neutral; outer conductor's $C=1{\cdot}25$.

(*iv*) In three-phase mesh or star system, pressure being given between any two-phase wires . . $C=2{\cdot}5$.

(*v*) In three-phase star system, pressure being given between outer and neutral . . . . . $C=0{\cdot}833$.

P. F. = power factor which is for lighting only = 0·95.

,, Mixed load, 2/3 light, 1/3 motor = 0·9.

,, Mixed load, 1/3 light, 2/3 motor = 0·85.

,, Motor load only = 0·8.

Area = $\text{kW} \times l \times C/E_r^2 \times P \times$ P.F.

(1) Current = watts delivered/E_r, for continuous current.

(2) For single-phase system, Current = watts delivered/$E_r \times$ P. F.

(3) Current = watts delivered/($E_r \times \sqrt{3} \times$ P. F.) for three-phase system.

Note that in practice it is seldom advisable to use a smaller wire than No. 6 S. W. G.

2-phase 4-wire system each conductor = 2·5.

2-phase 3-wire, voltage being taken between outer and neutral, = 2·5.

2-phase 3-wire common = 3·54.

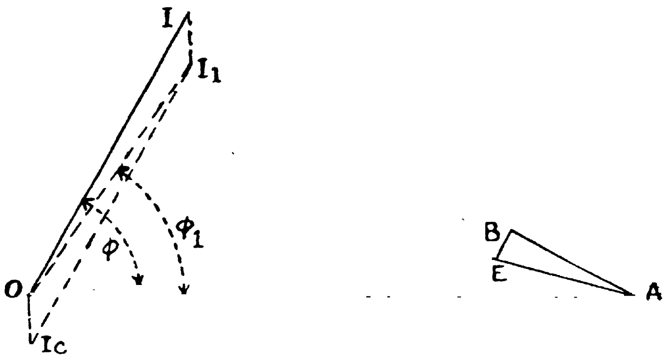
3-phase mesh connection, volts taken between conductors, = 2·5.

461. Feeding Point:—The point at which a system of mains should be fed is the point where the feeders are attached to the mains; it is necessary to find the electrical centre of gravity of the system. The method used is similar to that used in determining the best location of a power plant as regards amount of copper required and consists of separately obtaining the centre of gravity of straight sections and then determining the total resultant and point of application of this resultant of the straight sections to locate the best point for feeding.

***462. Graphical Construction of Single-Phase Lines**:—Draw to any scale the vector OE to represent

* J. W. Meares.

the voltage at the receiving end of the line, and the vector *OI* to represent the current in magnitude and direction, the angle ϕ between *OE* and *OI* being that for which the power factor of the load is the natural cosine. The drop of pressure due to the ohmic resistance of the line is in phase with the current, and represented by *EB*, drawn parallel to *OI* to the same volt scale as *OE*.



Graphical Construction for Single-Phase Lines

Fig. 8·06.

The inductive drop is at right angles to the ohmic drop and this inductive drop is represented by *BA* drawn at right angles to *EB*. Join *AE*; then *AE* gives the impedance drop. Finally, *OA* gives the voltage at the generating end of the line on the same scale. The resultant or impedance drop *AE* is, as in the Figure 8·06 shown, out of phase with the receiving voltage; it is not exactly equal to the difference of the voltages at the sending and receiving ends of the line, but it may be safely taken so in ordinary work. When the charging current is of sufficient importance, as in long distance transmission, it must be taken into consideration with the main current. The main current lags behind the impressed voltage by an angle depending on power factor, while the charging current is leading the E. M. F. by 90°.

Now OA and OE are the pressures at the generating and receiving ends of the line, respectively, and OI is the lagging energy current.

The charging current OI_c is drawn to the same scale, leading, at right angles to OE or better still OA. Then composing OI and OI_c the resultant current OI_1 is found; then EB should be drawn parallel to OI_1 instead of OI. The angle ϕ_1 will give the power factor at the generating end.

Comparison between Single-phase and Three-phase Transmission

Example 5. 952 kW. at 80 per cent. power factor has to be delivered at the end of a single-phase 6-mile line at 6,285 volts and 50 cycles. The size of the wires is 5/0 S.W G. and is spaced 2′-6″ apart. Find the voltage in the generating station and the power loss in the line.

Solution :—

The resistance of this wire = 0·294 ohm per mile.

The reactance at 50 cycles = 1·67 ohms per mile.

$$\text{The current in the line} = \frac{952 \times 1{,}000}{0{\cdot}8 \times 6{,}285} = 189{\cdot}3 \text{ amps.}$$

$$\begin{aligned}\text{The resistance drop in 12 miles} &= 12 \times 0{\cdot}294 \times 189{\cdot}3 \\ &= 668 \text{ volts.} \\ \text{The reactance drop in 12 miles} &= 189{\cdot}3 \times 12 \times 1{\cdot}67 \\ &= 3{,}800 \text{ volts, nearly.}\end{aligned}$$

The voltage at the generating station = E_0

$$= \sqrt{(6{,}285 \times 0{\cdot}8 + 668)^2 + (6{,}285 \times 0{\cdot}6 + 3{,}800)^2}$$

$$= \sqrt{(5{,}696)^2 + (7{,}571)^2}$$

= 9,480 volts, nearly

$$\begin{aligned}\text{Power loss in the line} = I^2R &= 668 \times 189{\cdot}3 \text{ watts.} \\ &= 127 \text{ kW., nearly}\end{aligned}$$

952 kW. at 80 per cent. power factor has to be delivered at the end of a three-phase 6-mile line at 6,285 volts and 50 cycles. The size of the wire is No 5/0 S.W.G. and spaced 30 inches apart. Find the voltage in the generating station and the power loss in the line.

Solution :—

The resistance in the wire = 0·294 ohm per mile.

The reactance in the wire = 1·67 ohms per mile.

$$\text{The current in the line} = \frac{952 \times 1{,}000}{0{\cdot}8 \times 1{\cdot}73 \times 6{,}285}$$

$$= 109{\cdot}4 \text{ amps.}$$

The line voltage to neutral $= 6{\cdot}285/\sqrt{3} = 3{,}630$ volts.

The resistance drop in 6 miles of wire $= IR$

$$= 109{\cdot}4 \times 0{\cdot}294 \times 6$$

$$= 193 \text{ volts.}$$

The reactance drop in 6 miles of wire $= IX$

$$= 1{\cdot}67 \times 6 \times 109{\cdot}4$$

$$= 1{,}095 \text{ volts.}$$

The line voltage in neutral at generating station

$$= \sqrt{(3{,}630 \times 0{\cdot}8 + 193)^2 + (3{,}630 \times 0{\cdot}6 + 1{,}095)^2}$$

$$= \sqrt{(2{,}904 + 193)^2 + (2{,}178 + 1{,}095)^2}$$

$$= \sqrt{(3{,}097)^2 + (3{,}273)^2} = 4{,}500 \text{ volts, approximately.}$$

The voltage between lines $= 4{,}500 \times 1{\cdot}73 = 7{,}800$ volts, approximately.

Power loss in the line $= 3 \times (109{\cdot}4)^2 \times {\cdot}294 \times 6$

$$= 63{\cdot}2 \text{ kW., nearly.}$$

463. Three-Phase Transmission.

***Example 6**. A transmission line delivers 952 kW. at the end of the three-phase three-wire line at a distance of 6 miles. The delivery pressure to be 6,285 volts and the loss in transmission to be 5 % (Example 1) of the power delivered.

Area of each conductor in square inches

$$= \frac{952 \times 6 \times 1{,}760 \times 2{\cdot}5}{6{,}285 \times 6{,}285 \times 5 \times \text{P. F.}}$$

$$= 0{\cdot}127/\text{P. F.}$$

*Proposed Benares Lighting Scheme.

	P. F. unity	P. F. 0·9	P. F. 0 8
Area of each conductor sq. in.	0·127	1·411	1·588
Weight in lbs. per yard =area × 11·56	1·468	1·631	1·835
Total weight of 6 × 1,760 × 3 yds.	46,500	51,680	58,130
Current in each conductor in amperes ...	87·4	97·1	109·4

The current = watts delivered/$V \times \sqrt{3} \times$ P. F.
= 952 × 1,000/6,285 × 1·732 × P. F.

As the loss is 5 %, 1,000 kW. will be put into it and the initial pressure will be (1,000 × 1,000)/($\sqrt{3} \times I \times$ P. F.) or about 6,600 volts in each case.

The pressure between the conductors is 6,285 V at the receiving end, and the pressure between any one wire and the neutral point will, therefore, be 6,285/$\sqrt{3}$, or 3,630 V. Let us consider one of the three conductors in the 1st place. Each conductor will deliver one-third of the total power or 317·3 kW. Take the case where the power factor is 0·9, the apparent energy delivered by each branch will be 317·3/0·9 = 352·5 K. V. A. and the current in the branch will be 352·5 × 1,000/3,630 = 97·1 amps., as already found by another method. Now as the loss of power is to be 5 % of that delivered, the energy component of the drop in pressure in each branch, or IR, will also be 5 % of the pressure to neutral; 5 % of 3,630 is 181 volts. The line current is in phase with this component of the total drop of pressure in the wire, so the loss of energy in each conductor will be $I \times E$ = 97·1 × 181 = 17·5 kW., thus the actual energy loss in the three branches is 52·5 kW. The ohmic resistance of each branch must be volts lost/current = 181/97·1 = 1·86 ohm for 6 miles of wire. Loss in each branch is also equal to $I^2R = (97{\cdot}1)^2 \times 1{\cdot}86 = 17{\cdot}5$ kW. as before, the resistance per yard = 1·86/6 × 1,760 = 0·000175 ohm.

Area of conductor = 0·00002453/0·000175 = 0·14 sq. in. (about 5/0 S. W. G.); weight = 1·695 lbs. per yard.

To find the inductance and reactance of the line, spacing of wire 30 inches.

The diameter of the wire = 0·432 in.

The radius = 0·216 in.

Self-induction $= 0·0805 + 0·741 \log_{10} (30/0·216)$ per mile = 1·67 mH per mile or 10·02 mH for 6 miles.

Reactance = 3.16 ohms.

Impedance $= \sqrt{(1·86)^2 + (3·16)^2} = 3·66$ ohms.

The power factor being 0·9, the induction factor is 0·436.

Hence, make the following table, giving the various voltages, etc., in one wire :—

	Voltage.		
	Energy Component.	Inductance Component.	Power.
At delivery end Energy component 0·9 of 3,630 volts.	3,268	...	Power delivered 3,268 × 97·1 = 317·3 kW. per branch or 952 kW. altogether.
Induction component 0·436 of 3,630 volts.	...	1,583	
In line—			
Resistance or energy loss IR = 97·1 × 1·86.	181	...	Power lost 181 × 97·1 = 17·5 kW. per branch or 52·5 kW. altogether.
Reactance loss = 97·1 × 3·16.	...	306·8	Impedance drop $= \sqrt{(1·81)^2 + (3.068)^2}$ = 355·4 which also = 3·66 × 97·1 = 355·4 volts
Total ...	3,449	1,889·8	Power generated = 3,449 × 97·1 = 335 kW. nearly per branch or 1,005 kW. altogether.

The generator pressure will be $\sqrt{\{(3{,}449)^2+(1{,}889\ 8)^2\}}$ $=3{,}932{\cdot}8$ volts to neutral which multiplied by $\sqrt{3}$ or $1{\cdot}73$ gives 6,804 volts between phase wires.

The power required to drive a single generator to give the output required assuming an efficiency of 93 per cent. would here be $(1{,}005/{\cdot}746)\times(100/93) = 1{,}484$ B. H. P.

Now the effect of self-induction in the line is to alter the power factor, or the phase relation of current and pressure. The total power at any point in a three-phase line is $I\times E\times\sqrt{3}\times$ P. F., which is here 1,005 kW. $I=97{\cdot}1$ and $E=6{,}804$ volts ; therefore, the power factor is $0{\cdot}875$ instead of 0 9 at the generator end of the line.

Hence, the output of the generator would be specified as 1,150 K. V. A., *i.e.*, $1{,}005/0{\cdot}875$, the denominator being the power factor as just shown.

Note that the wire corresponding to the resistance, *i.e.*, $0{\cdot}31$ per mile, is not marketable, the nearest size is 5/0 S. W. G. whose resistance is $0{\cdot}294$ which gives lesser power loss in the line.

The whole calculation should be done again accordingly in practical work.

Ayrton's Formula :—

If i = rate of interest on money value of conductor,
a = cost in pounds of a ton of copper,
s = resistance of a mile of conductor one square inch in section.

$$t = \sqrt{67{\cdot}84\frac{ias}{b}} \text{ from Thomson's formula,}$$

b = annual cost in pounds of an electric horse-power for the number of hours the power is required,

r = resistance per mile of conductor,
n = total length of conductor in miles,
V = potential difference at generator.

P_w = watts to be furnished at the end of line. Then Prof. Ayrton's formula for the most economical current density in a given conductor with a given difference of potential at the generator is—

$$I = \frac{t}{r} \frac{\sqrt{V^2 + n^2 t^2} - nt}{V}$$

$$or, \quad I = \frac{P_w}{V} \left\{ 1 + \frac{nt}{\sqrt{V^2 + n^2 t}} \right\}$$

***Graphical Solution of Three-Phase Problems** :— Draw an equilateral triangle ABC, the sides of the triangle representing to scale the pressure between the phases at the loaded end. Join the points A, B and C to O, the centre of the triangle; thus OA, OB and OC represent the pressure to the neutral (line pressure $/\sqrt{3}$).

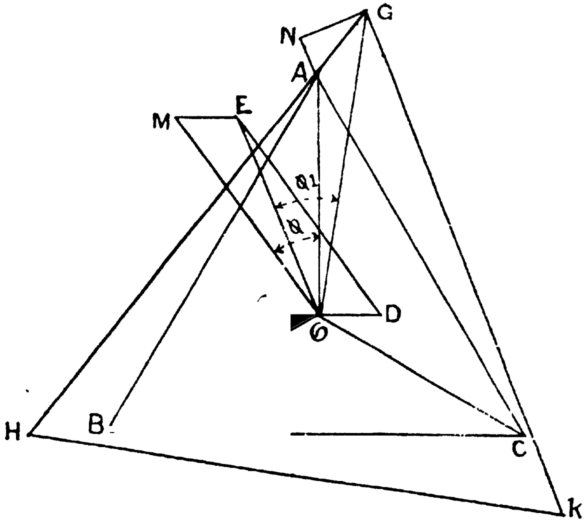
Draw OM representing to scale the full-load current lagging behind OA by the angle ϕ. Draw OD at right angles to OA to represent the capacity current to the same scale as OM.

Draw OE the resultant of OD and OM. OE represents the resultant current and the resistance drop in one wire is in phase with the current OE and its value is given by $OE \times R$. Its value is represented to the same scale of volts as before by AN drawn parallel to OE. Now draw NG to the same scale and at right angles to AN to represent the E. M. F. of self-induction or reactance drop in one wire.

Join OG which gives the pressure to neutral at the generating end, this supplemented by $\sqrt{3}$ gives the pressure between phases at that point.

* J. W. Meares' Electrical Engineering Practice.

The sides of the equilateral triangle GHK completed



Graphical Construction for Three-phase Line.

Fig. 8·07.

from the centre O and vertex G also give this. $Cos\ \phi_1$ is the power factor at the generating end, and the kW delivered to the line will be pressure $GH \times \sqrt{3} \times$ amp. $OE \times cos\ \phi_1$.

464. Determine the form factor when the load factor and annual $I_{R.M.S.}$ current are given :—

$$I_{R.M.S.} = \frac{m}{100} \times I \times q$$

where I_{RMS} = annual R.M.S. current in amperes.

I=full load current in amperes.

m=annual load factor of the line expressed in percentage.

q=form factor.

$$= \frac{I_{\text{R.M.S.}}}{\text{Annual mean current}}$$

Approximate values of V for various values of m :—

Load factor m o/o.	Form factor q.	Load factor m o/o.	Form factor q.
10	2·25	50	1·20
15	1·88	60	1·13
20	1·68	70	1·08
25	1·55	80	1·04
30	1·45	90	1·02
40	1·30	100	1

Example 7. Two three-phase transformers (or banks of single-phase transformers), each of 5,000 K.V.A. capacity, are provided both at the sending end and receiving end of the line. The line pressure is 22,000 volts, the load factor is 60 o/o, distance 20 miles and cycle 50, power factor 80 o/o. Determine (1) the economic current density for the line conductors, (2) the current required when the maximum load of 5,000 K.V.A. per set of conductors is being transmitted, (3) the economic section of the wire, (4) the weight of the conductors, (5) the cost of the conductors.

The cost of hard-drawn stranded copper conductor= as. -/9/- per lb.

The cost of wasted energy 0·5 anna per kilowatt hour.

The interest and depreciation on the cost of conductors as 12 o/o per annum.

Solution :—

Annual cost of interest and depreciation for copper

$$= \text{Rs. } \frac{a\,A\,L\,K}{16}\,r$$

$$= \text{Rs. } a\;\;A\;\;L\,r \times \frac{0{\cdot}312}{16}$$

Annual cost of lost energy :—

$$= \text{Rs. } \frac{I^2\,L\,\rho}{A} \times \frac{24 \times 365}{1{,}000} \times \frac{P}{16}$$

where a = cost of copper in annas per lb.
A = cross-section in sq. in.
L = total length of copper in inches.
K = weight of copper in lbs. per cubic inch.
= ·352 lb.
r = interest and depreciation per year on unity.
ρ = specific resistance per inch cube.
= 67×10^{6} ohm at 20° C.
p = cost of unit kW.-h. in annas.

(1) For the economical current density

$$a\;A\;L\;r \times \frac{0{\cdot}312}{16} = \frac{I^2\,L}{A} \times \frac{P}{16} \times \frac{24 \times 365}{1{,}000} \times {\cdot}67 \times 10^{-6}$$

$$\text{or, } \frac{I}{A} = \sqrt{\frac{0{\cdot}312 \times 10^9}{24 \times 365}} \times \sqrt{a\,r/\rho}$$

$$= 205{\cdot}5 \times \sqrt{\frac{9 \times {\cdot}12}{{\cdot}5}} = 302 \text{ amperes / per sq. in.}$$

(2) Average current $= \dfrac{5{,}000 \times 1{,}000}{\sqrt{3} \times 22{,}000} = 132{\cdot}55$ amps.

(3) Economic section f of the conductor

$$= \frac{89{\cdot}85}{302} = 0{\cdot}2975 \text{ sq. in.}$$

(4) The weight of copper conductor 1 mile long and 1 sq. in. cross-section is approximately 21,000 lbs.
∴ Total weight of copper required in the line is
$= \cdot 2375 \times 20 \times 21{,}000 \times 6 = 749{,}700$ lbs.

(5) The total cost of the line conductors on a 22,000-volt system is

$$= \text{Rs. } 749{,}700 \times \frac{9}{16}$$

$$= \text{Rs. } 421{,}143/12/\text{-}$$

Table—*Approximate relative costs of High-Tension Apparatus.*

66,000 volt costs taken as 100 °/o although the relative costs are liable to fluctuation. Get the true information from the manufacturers

Apparatus	VOLTAGE.							
	6,600	11,000	22,000	33,000	44,000	66,000	88,000	110000
Transformers	100	102	108	115	125	150	175	200
Switchgears	100	100	100	110	115	155	155	420
Electrolytic Lightning Arresters	100	151	205	320	408	640	1,600	1,900
Insulators ...	100	135	430	650	1,250	3,500	5,500	6,500

Now to determine the most economic voltage, add the price of (1) the transformer, (2) the switchgear, (3) line insulator. Compare the installation cost at various standard pressures together with other items and determine which pressure is most economical for the conditions laid down. Remember that greater and lower maintenance and operating costs may be obtained by designing the system for a high pressure; more trouble is experienced with heavy currents than with high voltages owing to the serious effect of transient disturbances due to switching or short circuits. When in doubt, select the higher voltage.

Example 8. Deduce the equation connecting the rate at which energy is delivered and the distance to which it will pay to transmit it under the following conditions. The energy is delivered at a constant rate for 12 hours a day, 300 days a year. Selling price of energy at station 1·5 as per kW.-h. and at the point of delivery 2 as. per kW.-h. The voltage at station is 500 D. C. and line efficiency is 90 °/o. Cost of copper 10 annas a pound The cost of line exclusive of copper is Rs. 2,000/- per mile. 15 °/o of the total cost of line is allowed as interest and depreciation per year. Find the maximum distance it will pay to transmit 100 kW. and the minimum energy it will pay to transmit over a distance of 1 mile.

Solution :—

Resistance of copper per mile $= \dfrac{0{\cdot}046}{A}$ ohms, where A is in sq. ins. Since efficiency is 90 °/o ; 10 °/o voltage drop is permitted in the line ; if R is the resistance of each wire ;

$R = \dfrac{0{\cdot}046}{A}\, l$ and $2RI = 50$ volts for any value of current I corresponding to power W.

Let C_1 be money realised from the delivery of a certain current I amperes at 450 volts.

$$\text{Then } C_1 = \frac{450 \times I \times 3{,}600}{1{,}000} \times \frac{2}{16} \text{ rupees per year.}$$

$$= \text{Rs. } 202\,5\; I$$

Let C_2 be the price of energy which is received at the receiving end at 1 5 annas per unit.

$$C_2 = \frac{500 \times I \times 3{,}600 \times 1{\cdot}5}{1{,}000 \times 16} = \text{Rs. } 168{\cdot}5\; I \text{ per year.}$$

C_3 the cost of energy lost in resistance is given by—

$$C_3 = \frac{2\,RI \times \iota \times 3{,}600 \times 1{\cdot}5}{1{,}000 \times 16} = \text{Rs. } 16{\cdot}85\; I \text{ per year,}$$

since $2\,RI = 10$ °/o of $500 = 50$.

If l is the length of the line in miles, the cost of the line would consist of two parts :—

First part.—C' the cost of line exclusive of copper which is independent of size of wire and **Second**—C'' is the cost of copper alone.

$C' = l \times 2{,}000$ Rs. (10 annas per lb.)

$$C'' = 2lA \times \sigma \times 36 \times 1{,}760 \times \frac{10}{16}$$

where A is the sectional area in square inches, and $\sigma =$ ·318 lbs. weight of one cubic inch of copper.

$$\text{We have } 2\,RI = 50, \qquad \therefore\ R = \frac{25}{I}$$

$$R \text{ is also } = \frac{0{\cdot}046}{A}\,l \quad \therefore\ A = \frac{I}{25} \times {\cdot}046l$$

$$\therefore\ C'' = 2l\left(\frac{I}{25} \times {\cdot}046l\right){\cdot}318 \times 36 \times 1{,}760 \times \frac{10}{16} \text{ rupees.}$$

Annual cost of the line

$$C_4 = \frac{15}{100}\ (C' + C'')$$

$$= {\cdot}15\left(2{,}000\,l + 2l^2 I\frac{{\cdot}046 \times {\cdot}318 \times 36 \times 1{,}760 \times 10}{25 \times 16}\right)$$

$$C_4 = \left(300l + 6{\cdot}98l^2 I\right) \text{ rupees per year.}$$

Now if the concern is to be paying at all

C_1 must be greater than $C_2 + C_3 + C_4$;

$C_1 > C_2 + C_3 + C_4$

or, $C_1 - C_2 - C_3 - C_4 > 0$

$17{\cdot}15\ I - 6{\cdot}98l^2 I - 300\ l > 0$

This equation gives relation between load and distance over which it may be delivered.

Now if the load is 100 kW., the current will be

$$\frac{100 \times 1{,}000}{450} = 222{\cdot}2 \text{ amperes.}$$

The longest distance over which this current can be delivered is given by—

$$17{\cdot}15 \times 222{\cdot}2 - 6{\cdot}98 l_1^2 \times 222{\cdot}2 - 300\ l_1 = 0$$

If the distance exceeds this value, the left-hand side will become negative and there will be a loss.

$$l_1 = \frac{-1{\cdot}35 \pm \sqrt{(1{\cdot}35)^2 + 478}}{2 \times 6{\cdot}98} = 1{\cdot}47$$ taking positive value only.

For a distance of 1 mile the minimum current is given by—

$$17{\cdot}15\ I_1 - 6{\cdot}98 \times I - 300 = 0$$
$$10{\cdot}17\ I_1 - 300 = 0$$

$$I_1 = \frac{300}{10{\cdot}17} = 29{\cdot}5 \text{ amperes (nearly)}$$

This corresponds to a load of $\frac{29{\cdot}5 \times 450}{1{,}000} = 13{\cdot}275$ kW.

Example 9. In a three-phase transmission line, each wire of which has 1·5 ohms resistance and 2 ohms reactance, the full load is 3,000 kW. at 86·6 per cent. power factor. The full load voltage at the receiving end is 6,600 volts. Find the voltage of the load when several of the induction motors, which constitute part of the load, are starting simultaneously, and lower the power factor to 75 per cent. at the same time increasing the load to 3,200 kW.

Solution —

The first step is to find the voltage at the sending end from data of normal conditions. This is done as in all previous examples of this chapter.

$$P = \sqrt{3} E\ I \cos\phi$$

$$I = \frac{3{,}000{,}000}{1{\cdot}73 \times 6{,}600 \times 0{\cdot}866} = 303{\cdot}5 \text{ amperes}$$

Resistance drop $= 1{\cdot}5 \times 303{\cdot}5$
$= 455$ volts (*say*).

Reactance drop $= 2 \times 303{\cdot}5$
$= 607$ volts.

Voltage to neutral $= \frac{6{,}600}{1{\cdot}73} = 3{,}810$ volts.

Construct a diagram as in Fig. 8·08 and solve for OS, the voltage to neutral at the sending end,

$$OS = 4{,}517 \text{ volts.}$$

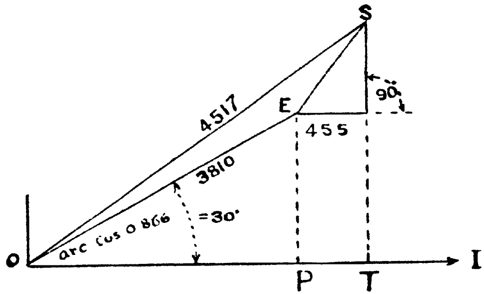


Fig. 8·08.

With the usual method of operation, a voltage to neutral of approximately 4,517 volts at the sending end would be maintained under all conditions.

The second step is to find what the voltage to neutral at the sending end would have to be, if the voltage at the receiving end were to remain 6,600 volts, or 3,810 volts to neutral, under the new condition of load and power factor.

$$P = \sqrt{3}\, EI \cos\phi$$

$$I = \frac{3{,}200{,}000}{1·73 \times 6{,}600 \times 0·75} = 380 \text{ amperes.}$$

Resistance drop $= 1\ 5 \times 380 = 570$ volts.
Reactance drop $= 2 \times 380 = 760$ volts.

Construct a diagram as in Fig. 8·09 and find the value of OS, the voltage to neutral at the sending end,

$$OS = 4{,}692 \text{ volts.}$$

Thus, the voltage to neutral at the sending end would have to rise to 4,692 volts in order to keep the voltage of the load up to 6,600 volts (3,810 volts to neutral) when the extra load at a low power factor was thrown on.

But the conditions at the sending end are such that the voltage to neutral remain practically constant 4,517 volts at all loads. Therefore, if the sending voltage

remains constant, the voltage at the receiving end must

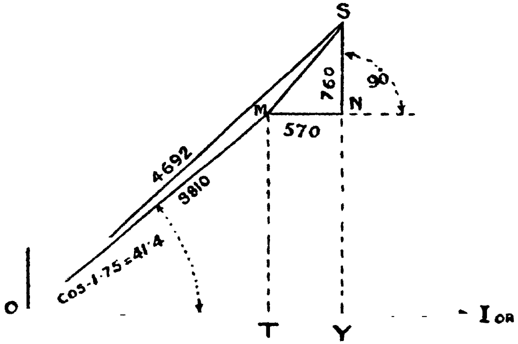


Fig. 8·09.

fall on account of the extra line drop between the generator and the load.

As a third step, we may then consider that the voltage to neutral of the sending end drops from 4,692 volts to 4,517 and compute the corresponding drop in the load voltage, from 6,600 to $\left(\frac{4,517}{4,692} \text{ of } 6,600\right)$, or 6,324 volts.

As a check on this value we have merely to compute what the generator voltage would have to be in order to maintain a voltage of 6,324 volts (3,655·5 volts to neutral) at the receiving end when loaded with 3,200 kW. at 75 per cent. power factor.

The check value is 4,560 volts to neutral, showing an error of about 1·5 per cent.

The error in this method lies in the fact that in the second step we have used too small a value for the line current. We may, therefore, better our result by repeating the second and third steps using a value for the line current, which we now know is more precise, as found by the equation :—

$$I = \frac{3,200,000}{1{\cdot}73 \times 6,324 \times 0{\cdot}75} = 390 \text{ amperes.}$$

The vector OS represents the sending voltage for a load voltage OE, over a line having a resistance voltage of ER and a reactance voltage RS, when the power factor of the load is 85·6.

By using 390 instead of 303·5 amperes for the line current, we find that it would require a generator voltage to neutral of 4,740 volts to maintain 6,600 volts between terminal at the load. With the generator voltage to neutral remaining 4,517, the load voltage would be $\frac{4{,}517}{4{,}740} \times 6{,}600$, or 629 volts, with checks to within less than one per cent.

By repeating steps two and three a number of times, each time using a more precise value for the line current it is possible to obtain the load voltage to any desired degree of precision. For most practical work one such repetition is sufficient.

Vector OS represents the voltage across one coil at the sending end of line in Fig 8·09 ; OM, the voltage across one coil of the load ; MN, the resistance drop of one wire ; and NS, the reactance drop of one wire when the P. F. is 75 %.

Example 10. **Data of Cost** :—Station and equipment Rs. 400 per kW. Transmission line exclusive of copper, Rs 1,600 per mile. Copper on poles 9 annas per pound. Generation of energy at switchboard 0·5 annas per kW-h. Depreciation on the entire investment 8 % per year. The station is run at full load capacity 12 hrs. a day for 300 days in the year and each consumer is charged for his proportional share of interest and depreciation on the station and equipment. (This is fixed by the power delivered at the switchboard to the consumers' line). The station voltage is 600.

Determine the minimum selling price per kW.-h. for 600 kW. to be delivered over an independent line to a consumer 2 miles from the station in order that there may be a profit of 10 % on the entire investment. At what voltage would this power be delivered to the

consumers ? Weight per mile of copper wire $= \dfrac{A}{62 \cdot 5}$

Resistance per mile in ohms $= \dfrac{55{,}000}{A}$, where A is the cross-sectional area of the conductor in circular mils.

Solution.—

To deliver 600 kW to the consumer the station capacity should be 10 % more for the compensation of line loss, *i.e.*, $1 \cdot 1 \times 600 = 660$ kW.

$\therefore$ cost of station and equipment = Rs. $660 \times 400 =$ Rs. 2,64,000/- ; cost of transmission line exclusive of copper = Rs. $1{,}600 \times 2 =$ Rs 3,200/-

To find the Section of Copper by Kelvin's Rule :—

Annual cost of lost energy $= \dfrac{2\, I^2\, p\, t\, \rho\, l}{A}$ annas.

Annual cost of interest and depreciation =

$$\frac{i}{100} \cdot A\ L\ K \times 0 \cdot 312$$

where I = average current transmitted in amperes.

$\left.\begin{array}{l} L = \text{distance of transmission} \\ A = \text{cross-section of copper} \end{array}\right\}$ in inch units

t = time per annum during which transmission occurs in thousands of hours.

p = cost of generating energy in annas per B. O. T. unit.

i = percentage of interest and depreciation together.

K = cost of copper in annas per lb.

For economical section :—

The annual cost of lost energy = the annual cost of interest and depreciation

$$\frac{2\, I^2 p\, l\, \rho\, t}{A} = \frac{i}{100} \cdot A\ L\ K \times 0 \cdot 312$$

$$\text{or, } A^2 = \frac{2\, I^2\, p\, l\, \rho\, t \times 100}{i\, l\, K\, 0 \cdot 312} = \frac{2\, I^2\, p\, t\, \rho \times 100}{i\, K \times 0 \cdot 312}$$

Now $I=\dfrac{660\times 1{,}000}{600}=1{,}100$ amps. $t=\dfrac{12\times 300}{1{,}000}$

$$\text{or, } A^2=\frac{2\times 1{,}100^2\times 0{\cdot}66\times 10^{-6}\times 3{\cdot}6\times 0{\cdot}5\times 100}{8\times 9\times 0{\cdot}312\times 10^6}$$

$$=1{\cdot}1\times 1{\cdot}1\times {\cdot}66\times 1{\cdot}3\times 5\times 25=13$$

or, $A=3{\cdot}6$ sq. ins.

Weight of copper in the feeder

$$=\frac{3{\cdot}6\times 1{\cdot}27\times 10^6\times 2}{62\ 5}\text{ lbs.}$$

$$=0{\cdot}1463\times 10^6=146{,}300 \text{ lbs.}$$

Resistance of the wires $=\dfrac{55\times 2\times 1{,}000}{3{\cdot}6\times 1{\cdot}27\times 10^6}=\dfrac{0{\cdot}11}{3{\cdot}6\times 1{\cdot}27}$

$$=\frac{110}{4{,}572}\text{ ohms}$$

Cost of copper

$$=146{,}300\times\frac{9}{16}$$

=Rs. 82,293-12-0.

Total capital cost of the installation :—

=Rs. 2,64,000+ Rs. 3,200+ Rs. 82,293-12-0.
=Rs. 3,49,493-12-0

Cost of interest and depreciation per year

$$=(\text{Rs. } 3{,}49{,}493/12/\text{-})\ \frac{8}{100}$$

=Rs. 27,959/8/-

Cost of generation $=\text{Rs. } 660\times 300\times 12\times\dfrac{0\ 5}{16}$

=Rs. 74,250/-

Total annual running cost = Rs. 27,959/8/- + Rs. 74,250/-.
= Rs. 1,02,209/8/-

The income should be 10 % more than the total running cost and equals Rs. 1,02,209/8/- + Rs. 10,200/15/3
=Rs. 1,12,430/7/3.

Hence, minimum selling price per kW.-hour

$$=\frac{\text{Rs. } 1,12.430\text{-}7\text{-}3}{660\times300\times12}$$

$=$Re. 0-0-9 p.

Voltage drop in the line$=IR$

$$=1,100\times\frac{110}{4,572}\text{ volts.}$$

$=26\cdot5$ volts.

The voltage at which power is to be delivered to the consumers$=600-26\cdot5=573\cdot5$ volts.

The voltage drop is only $\frac{26\cdot5\times100}{600}=4\cdot4$ %

Example 11. Twenty thousand kilowatts are to be transmitted over a station of transmission line 30 miles long using a three-phase circuit of aluminium conductors with 110,000 volts at generating station. The various constants are :—Frequency$=50$, cost of power per kW. year$=$Rs. 36, cost of aluminium per pound $=$As. 12, interest rate thereon$=6$ %.

Determine the economic drop, cross-section of conductor, natural frequency of the line and charging current per conductor Prepare curves showing the vertical sag at different temperatures for various spans.

Economic drop in a 3-phase line is given by

$$X=-\tfrac{3}{4}\frac{K}{E^2 C_1}+\frac{I}{4E^2C_1}\sqrt{9K^2+12E^2C_1K}$$

Here $C_1=36$, $E=110{,}000$ and $K=p\,C_2 r\,w\,4L^2$. 1,000

$$=0\cdot06\times85{,}000\times0\,0048\times4\times30\times30\times1{,}000$$

$$=66{,}100{,}000.$$

$$X=-\tfrac{3}{4}\Big[66\cdot1\times10^6-\sqrt{66\,1\times66\,1\times10^{12}+\tfrac{4}{3}\times121\times10^8\times36\times66\cdot1\times10^6}\Big]\div110{,}000\times110{,}000\times36.$$

$$=0\cdot0105\text{ or }1\cdot05\ \%$$

Cross-section of conductor in circular mils,

$$A = \frac{1}{2}\left(\frac{1{,}000P}{E^2}\ \text{r.}\ \frac{2\,L}{X}\right)$$

$$= \frac{1}{2}\left(\frac{20\times10^6}{12{,}100\times10^6}\times 85{,}000\times\frac{60}{0\ 0105}\right)$$

= 1 million circular mils (approx.)

Natural frequency—

$$f = \frac{1}{4\sqrt{L\ C}}$$

Assuming a spacing of 72″ for this voltage,

$$L \text{ per mile per wire } = \left[80{\cdot}3+740\ log_e\frac{d}{R}\right]\times10^{-6}$$

Here, $d=72{,}000$ mils and

$R=\sqrt{4}$ million cir. mils.

$=2{,}000$ mils

$L=[80{\cdot}3+740\times2{\cdot}3\times\ log_{10}\,36]\times\ 10^{-6}$

$=0{\cdot}002732$ henry.

∴ total inductance of the line$=0{\cdot}002732\times30\times3={\cdot}249$

Line capacity per mile between one conductor and neutral plane is given by

$$C=\frac{{\cdot}0388}{log_e\frac{d}{R}}\text{ microfarads.}$$

$$=\frac{{\cdot}0388}{log_e\ 36}={\cdot}0108\text{ mfd.}$$

∴ total capacity$=0{\cdot}0108\times30\times3$

$=0{\cdot}972\times10^{-6}$ farad.

∴ Natural frequency $f=\dfrac{1}{4\sqrt{0{\cdot}249\ \times\ {\cdot}972\ \times\ 10^{-6}}}$

$=510.$

Charging current per conductor=voltage × capacity.

$=110{,}000\times{\cdot}972\times10^{-6}$

$={\cdot}10692$ amps.

Example 12. The potential differences at the load and generator ends of a transmission line are each 6,600 volts. The resistance of the line is 6 ohms and the reactance 8 ohms. If the line current is 100 amperes, find (*a*) the power factor at the load, and (*b*) the efficiency of the transmission line (Pender).

Solution :—

This case may happen in a circuit with *leading* current as shown in Fig. 8'10. Let OE represent the voltage at the load end, I the current leading by an angle ϕ, and E_z the impedance drop in the line. Then completing the parallelogram OEE_0E_z the diagonal OE_0 will represent the voltage E_0 at the generator end.

By the question—

$E=E_0=6,600$ volts.

$I\ =100$ amps

$R=6$ ohms, $X=8$ ohms.

$\therefore E_z=\sqrt{(RI)^2+(XI)^2}$

$=\sqrt{(600)^2+(800)^2}=1,000$ volts.

Now resolving E and E_z along and perpendicular to OI, we have—

Component along $OI=RI+E\cos\phi$.

Component perp to $OI=E\sin\phi-XI$.

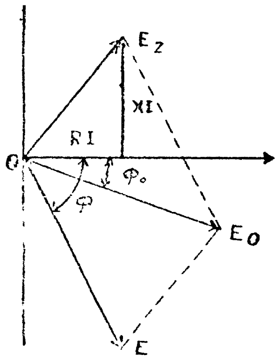


Fig. 8'10.

Then, we must have—

$$E_0{}^2=(E\cos\phi+RI)^2+(E\sin\phi-XI)^2$$
$$=E^2(\cos^2\phi+\sin^2\phi)+(R^2I^2)+X^2I^2)$$
$$-2\,EI\,(X\sin\phi-R\cos\phi).$$
$$=E^2+E_z^2-2\,EI\,(X\sin\phi-R\cos\phi).$$

$\therefore\quad X\sin\phi-R\cos\phi=E_z^2/2EI$, (since $E_0{}^2=E^2$),

or, $8\sin\phi-6\cos\phi=(1,000)^2/13,20,000=25/33$,

or, $0{\cdot}8\sin\phi-0{\cdot}6\cos\phi=25/330=0{\cdot}0757$,

$\therefore\quad \sin(\phi-\theta)=0{\cdot}0757$,

where $\sin\theta=0{\cdot}6$, $\cos\theta=0{\cdot}8$, *i.e*, $\theta=36°52'$.

$\therefore \quad \phi-\theta=4°\ 20'$.

$\therefore \quad \phi=41°\ 12'$.

Hence, the power factor at the load end,

or $\cos\phi=0{\cdot}762$ or $75{\cdot}2$ %.

The power factor at the generator end is given by

$$\operatorname{Cos}\phi_0=\frac{RI+E\cos\phi}{E_0'}=\frac{600+6{,}600\times0{\cdot}752}{6{,}600}$$

$$=0{\cdot}843 \text{ or } 84\ \%$$

Now, the efficiency of the transmission line is evidently

$$=\frac{\text{output}}{\text{input}}=\frac{EI\cos\phi}{E_0'I\cos\phi_0}$$

$$=\frac{\cos\phi}{\cos\phi_0}=\frac{0{\cdot}752}{0{\cdot}843}=0{\cdot}892 \text{ or } 89{\cdot}2\ \%.$$

Note that as the line may have both inductance and capacity, not concentrated but distributed along the line, it is possible for the load P.D. to be higher than the generator P. D. and that the P D. at an intermediate point may be higher than the P.D. at either end.

Example 13. The voltage at the receiving end of a 50-cycle three-phase transmission line, 14 miles long, is 6,600 between the lines. The line consists of three wires, No. O. S. W. G. (diameter = $0{\cdot}32$ cm), 30 inches (76 cms.) apart. and of specific resistance $\rho=1{\cdot}8\times10^{-6}$; what is the power received over the line, the power lost in the line, and the power put into the line ? Calculate the efficiency of transmission with non-inductive load of 50 amps per phase, with an inductive load of 30° lagging and an inductive load of 30° leading.

Solution :—

The power received per line with non-inductive load.

$P=EI=3{,}810\times50=190{,}500$ watts $=190{\cdot}5$ kW.

The power received per line with 30° phase displacement,—

$P=EI\cos 30°=3{,}810\times50\times\sqrt{3/2}=165$ kW.

The power lost per line $P_1 = I^2 R$
$= 50^2 \times 7{\cdot}64 = 19{\cdot}1$ kW.

Hence, the total input $P_0 = P + P_1$
$= 209{\cdot}6$ kW. at non-inductive load
$= 184{\cdot}1$ kW. at load of 30° phase displacement.

The efficiency with non-inductive load is given by

$$P/P_0 = \frac{190{\cdot}5}{209{\cdot}6} = 90{\cdot}9 \text{ per cent. and}$$

with a load of 30° phase displacement by

$$P/P_0 = \frac{165}{184{\cdot}1} = 89{\cdot}6 \text{ per cent.}$$

The total output $= 3P_0 = 571{\cdot}5$ kW. and 495 kW., respectively.

The total input $= 3\,P_0 = 628{\cdot}8$ kW. and $552{\cdot}3$ kW., respectively.

Example 14. The voltage at the receiving end of a three-phase long-distance transmission line, is 6,000 at no-load, and 6,600 at full-load of 100 amperes power component, and proportional at intermediary values of the power component of the current ; that is, the voltage at the receiving end increases in proportion to the load. At three-quarters load the current is in phase with the E.M.F. at the receiving end. The generator excitation, however, and thus the (nominal) generated E.M.F. is maintained constant at all loads, and the voltage regulation effected by producing lagging or leading currents with a synchronous motor in the receiving circuit. The line has a resistance $R_1 = 8$ ohms, and a reactance $X_1 = 4{\cdot}5$ ohms per wire. The generator is star-connected, the resistance per circuit being $R_2 = {\cdot}8$ ohm, and the (synchronous) reactance is $X_2 = 30$ ohms. What must be the wattless or reactive component of the current, and, therefore, the total current, and its phase relation at no load, one-quarter load, one-half-load, three-quarters load, and full-load ? What will be the terminal voltage of the generator under these conditions ?

Solution.—

In Fig. 8·11, let E represent the voltage at the receiving end of the line ; I_1 the power component of the

current I corresponding to the load, in phase with E; and I_2 the reactive component in quadrature with E, shown leading in Fig. 8·11 and lagging in Fig. 8·12. The total resistance of the line and generator, $R=R_1+R_2$ = 8 8 ohms. The total reactance, $X=X_1+X_2=34·5$ ohms.

The E.M.F. consumed by resistance $E_1=RI$, is in phase with I. The E M. F. consumed by reactance, $E_2=XI$, is 90° ahead of I.

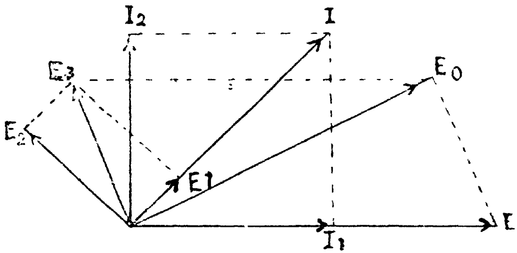


Fig. 8·11.

The E. M. F. consumed by impedance, $E_3=ZI$, where

$$Z=\sqrt{R^2+X^2}$$

Thus, E_3 combined with E, the receiver voltage, gives the generator voltage E_0.

Resolving all E. M. Fs. and currents into components in phase and in quadrature with the receiver voltage E,

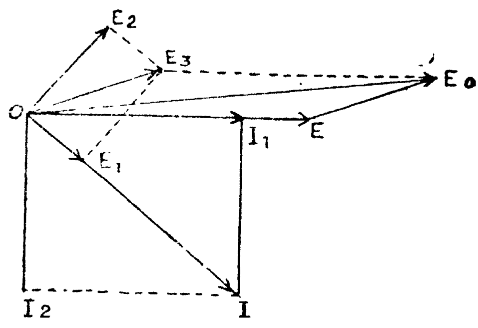


Fig. 8·12.

		Phase Component.	Quadrature Component.
current I	gives	I_1	$\pm I_2$
E. M. F. at receiving end of line, E,	,,	E,	0
E. M. F. consumed by resistance, E_1,	,,	RI_1,	$\pm RI_2$
E. M. F. consumed by reactance, E_2,	,,	$\pm XI_2$,	$\pm XI_1$

Thus, total E. M. F. or generator voltage,

E_0, gives $E + RI_1 \pm XI_2$, $RI_2 \pm XI_1$

The upper sign being taken for the leading and the lower for the lagging current.

The generator E. M. F., therefore, consists of two components giving the resultant.

$$E_0 = \sqrt{(E + RI_1 \pm XI_2)^2 + (XI_1 \pm RI_2{}^2)} \quad \ldots \quad \ldots \quad (1)$$

At three-quarters load, $E = 6{,}000 + 450 = 6{,}450$ volts. between lines $= \frac{6{,}450}{\sqrt{3}} = 3{,}724$ volts per line.

$I_1 = 75$ amperes, $I_2 = 0$.

Thus, $E_0 = \sqrt{3{,}724 + 8\ 8 \times 75)^2 + (34\cdot5 \times 75)^2}$
$= 5{,}090$ volts per line.

or, $5{,}090\sqrt{3} = 8{,}816$ volts between lines as (nominal) generated voltage.

Substituting the values of E_0. R and X in equation (I) we have :—

$$5{,}090 = \sqrt{(E + 8\cdot8\ I_1 - 34\cdot5\ I_2)^2 + (34\cdot5\ I_1 + 8\ 8\ I_2)^2}$$

from which I_2, and hence the total current $I = \sqrt{I_1^2 + I_2^2}$ at various loads can be determined if corresponding values of E and I_1 are known.

Thus, we construct the following table :—

	No load	1/4 load	1/2 load	3/4 load	Full load
Voltage between lines, $E\sqrt{3}$ =	6,000,	6,150,	6,300,	6,450,	6,600
Voltage per line, E =	3,464,	3,551,	3,637,	3,724,	3,811
Power component of current per line, I_1 =	0	25	50	75	100
Wattless component of current per line I_2 =	−46,	−38·5,	−22·3	0	36·2

The total current, $\sqrt{I_1^2+I_2^2}$

	$=46$	$45{\cdot}9$	$54{\cdot}8$	75	$106{\cdot}3$
The power factor, $I_1/I=\cos\phi$	$=0{,}54\ 5$	$91{\cdot}2$	100		94
The lag of current, ϕ	$=90^\circ$	57°	$24^\circ 10'$	$0,$	$-19^\circ 49'$

The generator terminal voltage per line is

$$E_1=\sqrt{(E+R_1\ I_1-X_1\ I_2)^2+(X_1\ I_1+R_1\ I_2)^2}$$

$$=\sqrt{(E+8\ I_1-4\ 5\ I_2)^2+(4{\cdot}5\ I_1+8\ I_2)^2}$$

Thus :—	No load	1/4 load	1/2 load	3/4 load	Full load
Terminal voltage per line, E_1	$=3{,}690$	$3{,}920$	$4{,}140$	$4{,}350$	$4{,}540$
,, ,, between lines $=E_1\sqrt{3}$	$=6{,}400$	$6{,}800$	$7{,}200$	$7{,}600$	$8{,}000$

Hence, at constant excitation the generator voltage rises approximately proportional to the load.

465. Regulation :—The regulation of a transmission line is the ratio of the maximum voltage difference at the receiving end, between rated non-inductive load and no-load, to the rated load voltage at the receiving end, constant voltage being impressed upon the sending end.

The impedance drop in the line voltage is consumed in the line impedance. It is the vector difference between the sending end voltage and the receiving end voltage. The pressure drop is the arithmetical difference between the sending and receiving end voltages. In lines where capacitance effects have to be reckoned with the regulation is greater than the pressure drop as the pressure rises due to the Ferranti effect.

The regulation is then the change of pressure at the receiving end, when the full load is thrown off, the sending end voltage being held constant

Let E=the voltage at the generating station,

E_t=the vector sum of the terminal voltage.

IR=the resistance drop,

IX=the reactance drop,

The phase relations between these voltages is shown in Fig. 8·13.

A vector I is drawn in any direction.

A vector E is drawn to scale equal to the receiver voltage, the angle ϕ depending on the resistance and inductance of the load connected to the line ;

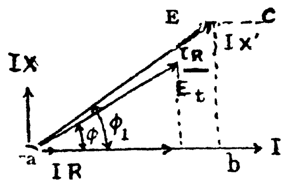


Fig. 8·13.

A vector $E=IR$ is drawn to scale in phase with I.

A vector $E_x=IX$ is drawn to scale in such a direction that I lags E_x by 90° degrees.

The vector E is the vector sum of E_t, E_r and E_x and may be scaled off or determined by calculation.

Since there is no power loss in the inductance of the line, the total loss is in the resistance and is equal to I^2R watts.

Example 15. 475 kW. at 6,300 volts and 50 cycles has to be delivered at the end of a 6-mile line, the size of the wire being 0000 S. W. G, and the spacing 30 inches. Find the voltage in the generating station and the power loss in the line if the load current is lagging and the power factor is 0·8.

watts$=E_t \times I \cos \phi$

$475 \times 1{,}000 = 6{,}300 \times I \times 0{\cdot}8$

and the current $=$ 94·25 amps.

The resistance $=$ 0·343 ohm per mile of wire.

$= 0{\cdot}343 \times 12 = 4{\cdot}1$ ohms for a 6-mile transmission.

The reactance $=$ 0·5 ohm per mile.

The reactance $=$ 6 ohms for 6 miles line.

$IR = 94{\cdot}25 \times 4{\cdot}1 = 386$ volts approximately $= 6$ % the receiving pressure.

$IX = 94{\cdot}25 \times 6 = 566$ volts approximately $= 9$ % of the receiving pressure.

Now $ab = (6{,}300 \times 0{\cdot}8) + 386 = 5{,}426$ volts.

$bc = (6{,}300 \times 0{\cdot}6) + 566 = 4{,}346$ volts,

$\therefore E = \sqrt{(5{,}426)^2 + (4{,}346)^2} = 6{,}951$ volts.

Power factor at the generating station $= ab/ac =$ $5{,}426/6{,}951 = 0{\cdot}78$.

Power put into the line $= 6{,}951 \times 94{\cdot}25 \times 0{\cdot}78$
$= 511$ kW.

Power delivered $= 475$ kW.

Loss in the line $= 511 - 475 = 36$kW.

and this is equal to $I^2R = (94{\cdot}25)^2 \times 4{\cdot}1$
$= 36$ kW. approximately

$$\text{Regulation} \quad = \frac{E_0 - E}{E} = \frac{6{,}951 - 6{,}300}{6{,}300} = 0{\cdot}1.$$

Percentage of regulation $= 10$.

466. Graphical Method of Determining Regulation.—

Let OE and OI represent the delivered voltage and current, respectively. The power factor of the load is assumed to be unity, the current and the voltage are in phase with each other.

Let E, E_1, E_2, E_3, be the voltages, and I, I_1, I_2, I_3, be the currents delivered to the load and the successive sections, respectively. Then if R and X be the resistance and inductive reactance in ohms, and C be the capacity in farads of each and every section.

$E_1 = (E + RI) + XI$ at 90° lead, vectorially

$E_2 = (E_1 + RI_1) + XI_1$ at 90° lead, etc., vectorially.

and $I_1 = I + \omega E\,C$ at 90° lead

$I_2 = I_1 + \omega E_1\,C$ at 90° lead etc.

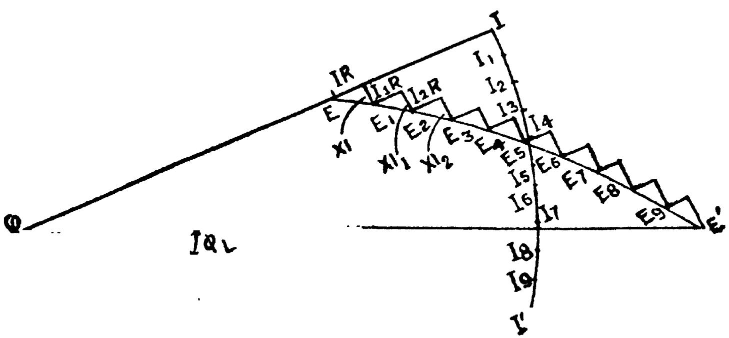


Fig. 8·14.

The various phase relations and magnitudes are seen in the Fig. 8·13.

The regulation of a three-phase circuit may be calculated by considering the three-phase circuit as equivalent to two single-phase circuits employing conductors of the same size. Thus the regulation of a three-phase circuit is the same as that of a single-phase circuit carrying half as much power with the same percentage loss, at the same voltage and distance between conductors.

467. Determination of Regulation with the Help of Mershon's Diagram:—By means of Mershon's diagram line drop calculation can be made which do not involve charging current effects. In Fig. 8·15 curves concentric with circles having radii E and E_t (Fig. 8·13) are drawn on a piece of squared paper from a centre which lies to the left of the diagram on the prolongation of the base line, but a considerable distance outside the diagram corresponding to the point "a." The radius of the inner circle is 10 or 100 divisions in length and the projection on the horizontal axis of any point B is cos ϕ and it indicates directly the power factor at the receiving end. By expressing the calculated resistance and reactive voltage drops as percentages of the receiving end pressure the scale may be applicable to any voltage, and the impedance triangle can readily be drawn to the proper scale and by making the spaces between the circles equal to the side of the squares on the divided paper, the regulation, or difference between generating and receiving pressures can be read off the diagram as a percentage of the receiving end pressure.

Example 16. Suppose a circuit of No. 4/0 wire spaced 30 inches carry a load of 500 amperes at a certain distance such that the power factor of the load is 0·77, resistance volts=17 per cent. of receiving end pressure. Reactance volts=22 per cent. of receiving end pressure. Determine the P. D between the generating and the receiving ends of the line.

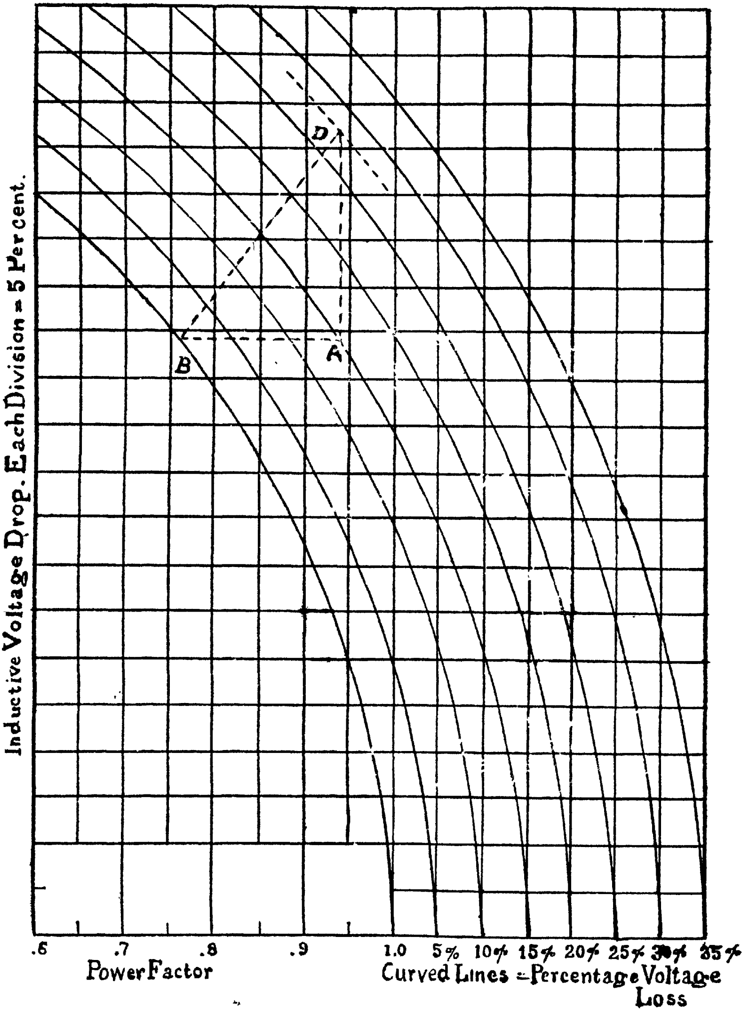

D
A
B
Inductive Voltage Drop. Each Division = 5 Per cent.
.6
.7
.8
.9
1.0
5%
10%
15%
20%
25%
30%
35%
Power Factor
Curved Lines = Percentage Voltage Loss

Fig. 8'15.

Solution :—The base of point 0·77 power factor line is the point R. The point B, where 0·77 power factor line intersects the first circle, is the point E_t of Fig. 8·13 passing from this point to the right 17 divisions and then upward 22 divisions a point D is reached which is a little below 30 per cent.; this point is equivalent to the point C. Thus from the division on the horizontal axis corresponding to power factor 0·77 follow the vertical ordinate until it meets the inner circle at D which lies on the dotted circle 27·5 divisions larger in radius than the inner circle (with radius=100 divisions). This indicates that the difference in pressure between the generating and the receiving ends on the line is 27·5 per cent. of the receiving end pressure.

468. Feeder Regulation *vide* **Ch. X for details** :—It may be done by (1) Booster, (2) Autotransformer and (3) Induction Regulator.

(1) *Booster* :—This is used on continuous-current circuits. It consists of a series generator driven by a shunt motor or some constant speed engine. Generally, it has two directly-coupled rotating armatures. The armature and the field of the generator are connected in series with the load. Any desired voltage may be obtained by properly proportioning the booster field. This is done because the voltage of the generator is proportional to the current flowing in the feeder and this voltage is added to the busbar voltage.

Disadvantage :—The efficiency is reduced and the operating complication is much enhanced.

(2) *Autotransformer* :—By connecting an autotransformer as shown in Fig. 8·16 we get the desired number of effective turns in the secondary by changing the position of the switch. *Disadvantage* :—This changes the voltage by definite steps according to the change or the number of turns in the secondary.

(3) *Induction Regulator* :—This is essentially an autotransformer in which the angular relations of the primary and secondary coils may be changed. Structurally the polyphase induction regulator resembles the polyphase induction motor with a wound rotor. The

single-phase one differs both in principle and in structure from the polyphase regulator.

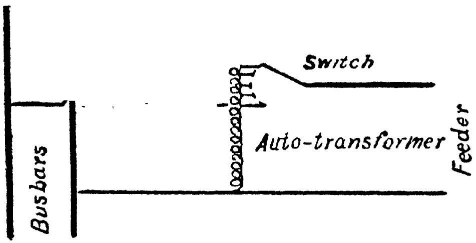


Fig. 8·16.

469. Line Conductors :—

(*a*) *Properties of Line Conductors* :—Electric circuits in general possess four fundamental electrical properties —resistance, inductance, capacitance and *leakance.* The last two depend in part upon the external dimensions of the conductors and their distance from one another and from other conducting bodies, and in part upon the dielectric properties of the materials employed for insulating purposes.

The inductance is a function of the magnetic field established by current in a conductor, but this field as a whole is divisible into two parts, one being wholely external to the conductor and the other being wholely within the conductor ; only the latter portion can be regarded as corresponding to the magnetic properties of the conductor material.

The resistance is strictly a property of the conductor itself. Both the resistance and the internal inductance of the conductors change in effective values when current changes with great rapidity, as in the case of high frequency alternating currents ; this is termed the 'skin effect.'

Conductors for outdoor overhead lines are subjected to various mechanical stresses. Consequently, their chemical composition, weight, tensile strength and elastic properties require consideration in all applications

as overhead conductors. They are effected by changes in temperature and by the conditions of mechanical stress to which they are subjected in service. They are also affected by the nature of the mechanical working and the heat treatment which they receive in the course of manufacture or fabrication into finished products.

Stranded Conductor ·—Unless the required section is very small, a stranded conductor should be used. *Advantages*:—(1) Great flexibility and thus allows easy handling ; (2) less fatigue by constant swinging than solid wires of large size.

The number of wires in each layer is an exact multiple of six and the total number equal to $1+3x(x+1)$, where x is any whole number.

Skin Effect :—This occurs when conductors carry currents whose intensity varies rapidly from instant to instant. This is due to the elements or filaments of variable current at different points in the cross-section of a conductor encountering unequal components of inductance ; but the central or axial filament meets the maximum inductance and in general the inductance offered to other filaments of current decreases as the distance of the filament from the axis increases, becoming a minimum at the surface or the periphery of the conductor. This, in turn, tends to produce unequal current density over the cross-section as a whole. The density is minimum at the axis and maximum at the periphery. Such distribution of the current density produces an increase in effective resistance and a decrease in effective internal inductance. The former is of more practical importance than the latter.

Proximity Effect :—When two conductors carrying current are very near each other, the flux due to one cutting the near half of the other is greater than the further half, and consequently the current distribution in that conductor is distorted. This is known as the proximity effect and it, like skin effect, increases the resistance and decreases the internal inductance of a conductor. Conductors of bigger section and lying closer are more subjected to this phenomena. This can be

ignored in the case of the transmission lines having wide spacing.

The proximity effect is practically eliminated in the stranded conductors as each strand of the conductor alternately passes through stronger and weaker field.

Sprirality Effect :—The phenomenon is caused by the current following, to a large extent, the spiral path of the individual wires, so that the conductor may be regarded as built up of a series of coaxial solenoids. Each of the solenoids formed by the consecutive layers produces a magnetic field whose direction is along the axis of the solenoid, *i.e.*, the axis of the conductor. The outermost layer contains the greater number of wires so that its field will be stronger than that due to the other layers. The next layer is spiralled in the opposite direction and contains fewer wires than the outer layer, so that there is produced a weaker field in the opposite direction. Owing to the reversal of spirality, the layer below gives rise to still weaker field in the original direction, and so on The resultant effect is, that travelling in a radial direction from the surface of the conductor the axial magnetic field alternates in magnitude although it does not actually change in direction on passing from one layer to another. As the potential difference applied to the ends of all the layers is the same, the variation in the axial magnetic flux leads to phase differences among the currents in consecutive layers. Hence, the sum of the R. M. S. values of the currents in the various layers may be appreciably larger than R M. S. value of the total current passing along the conductor, or in other words, the resistance of the conductor has been apparently increased.

**Conductor Material* :—The physical properties of *copper conductors* are universally known, their behaviour as overhead conductors has been studied through many years of practice, and they have a well-established reputation for reliable and efficient operation. Since aluminium is appreciably cheaper than copper, however, the use of

* E. T. Painton's Mechanical Design of Overhead Electrica Transmission Line.

this metal has made considerable headway, and it appears that, when suitably erected, aluminium conductors are as reliable as copper. The cost of the conductors themselves is not the only factor to be taken into consideration, and, before choosing aluminium in place of copper a careful examination must be made of the effect upon the cost of the other parts of the line. *Aluminium wires* being of larger diameter than copper of equal conductance, the corona loss is less ; the wind pressure upon the conductors will be large, and the support must, therefore, be stronger. Moreover, the lower tensile strength of the metal will necessitate a large sag, and hence a higher support for the same ground clearance. The saving on the cost of the conductors may, therefore, be offset to some extent by additional cost of supports.

It now appears to be well-established that for small sizes of conductors the use of aluminium is uneconomical, and that the chief field for plain aluminium conductors is for heavy current transmission, where the conductors' size is large and its cost forms a large proportion of the total cost of the complete installation. With such conductors, also, the smaller tensile strength of aluminium becomes of small account, since in either case the ultimate load of the conductor would be so large that it becomes impossible to take full advantage of this in adjusting the working tension.

Steel-cored aluminium conductors are obviously more expensive than plain aluminium conductors, but they are usually cheaper than copper of equal conductance, and are considerably stronger. They are being used very largely for high-voltage long-distance transmisson in which the supports are rigid steel structures and the span lengths are long. The cost of the supports in such a case depends chiefly upon the longitudinal tension in the conductors and upon the support height, the latter, of course, being influenced very greatly by the sag of the conductors between the supports.

It is found that the maximum sag with a steel-cored aluminium conductor is less than that of an equivalent copper conductor erected under the same conditions, so

that with steel-cored aluminium a smaller support height is required for the same span length. On the other hand, the supports will be subjected to a greater loading. Now the weight of a support increases in direct proportion to an increase in load, but increases much more rapidly with increase in height. Hence, if the span is long, so that the sag forms a large proportion of the total support height, it is possible that the reduction in height due to the use of steel-cored aluminium conductors will more than compensate for the increased load, and result in a lighter support. On the other hand, if the span length is short, so that the reduction in sag forms but a small proportion of the total height, the supports for steel-cored aluminium conductors will be heavier and more costly. It follows, therefore, that steel-cored aluminium conductors are not well adapted for short span lengths, but may show appreciable economies both on the cost of conductors themselves and also on the cost of the supports when the span lengths are long.

A preferable method of making use of the better mechanical properties of steel-cored aluminium in comparison with copper is to increase the span length so as to keep the same support height. The cost of each individual support is then greater with steel-cored aluminium than with copper, since the increased loading is not compensated by a reduced height, but as the total number of supports required will now be less, the total weight of steel required will probably be smaller, and, in addition, a smaller number of insulators is required, and the cost of erection is reduced.

Copper-clad steel conductors have not yet been adopted to the same extent as the other three conductor types considered. For the same conductance they are much more expensive, but they are useful when a conductor of small size must be erected upon a very long span length. There is a practical lower limit to the size of copper wire, which can be erected upon any span length, owing to the rapid increase in sag as the diameter is reduced For earth wire erected below or above power conductors, only a small current-carrying capacity is required, and as the size of copper necessary for this is

usually too small for erection upon the span length suitable for the large power conductors, such earth wires are often of galvanised steel. Copper-clad steel forms a useful substitute for galvanised steel in such cases, since it is free from the danger of corrosion. For similar reasons copper-clad steel has been employed for overhead telegraph lines, and for power conductors when exceptionally long span lengths are necessitated by river, gorge and other crossings.

Some particulars of conductor materal other than copper :—

(1) Aluminium—Conductivity 60 %; temperature coefficient of resistance 0·00390 ;

Density = 2·71 grammes per cu. cm.
Ultimate strength 75 % of copper
1·26 times of copper conductor of equal resistance.

Linear coefficient of expansion is 1·4 times of copper, and so greater sag of copper.

(2) Steel-cored Aluminium—Weight 25 % smaller with less sag than copper ; require smaller poles.

(3) Copper-clad Steel—Conductivity 30 to 40 % of copper—very suitable for river crossing or where long spans are desirable.

(4) Cadmium Copper—1 to 2 % of cadmium,—the increase of tensile strength is by 80 % ; conductivity only reduced by 20 % below that of pure copper.

(7) Iron or steel is most advantageous where the copper conductor form would be smaller than 8 S W.G. and would be unsuitable for use for lack of mechanical strength.

470. Underground Cables Used in Practice :—Usually the 3-conductor cable is preferred for 3-phase transmission and distribution. When installed on a star-connected distributive system, a bare neutral is frequently satisfactory. For higher voltage single conductor cables are found often necessary on account of the excessive weight and diameter of multicore cables. Use of multicore cables effects a saving in duct space,

when the drawn-in system is used ; but the objection is that one fault on the cable may cause an interruption of service on several circuits.

Concentric stranded conductors are used almost exclusively for underground cables of sizes above No. 6 S.W.G. ; very large sizes are often stranded over a non-conducting core to reduce skin effect.

The failure of a system may be due to system disturbances or over-voltage, exposure to external sources of heat, electrolysis and mechanical injury.

The current-carrying capacity of a cable is increased by making cables with larger conductors and insulation which would withstand higher temperatures and possess lower dielectric losses at operating temperatures and lower thermal resistivity.

The loads in central stations have now reached a condition, when a mere increase in current-carrying capacity will not solve the cable problem. Therefore, increased power capacity must be obtained by increasing the pressure. The means adopted are :—

(1) Use of single-conductor cables on 3-phase systems.

(2) Shielding of conductors to prevent internal corona.

(3) Use of oil and paper of increased dielectric qualities.

(4) Improvement of impregnation and other manufacturing processes.

(5) Reduction of dielectric losses.

(6) Increase of permanence of dielectric under stress.

Grade of Cables :—Electric wires and cables are sold as being of a certain grade of insulation resistance. The three most generally used grades are 300, 600 and 2,500 megohm grades. These figures represent the minimum insulation resistance per mile of the largest size of the cables in each grade. Thus, in 600 megohm grade cables, from about 19/15 S. W G. upwards will have actually this resistance per mile ; smaller cables of this grade insulated to the same specification will have higher resistance up to 1,200 or 2,000

megohm/mile in the smallest sizes. This is due to the reduction in wire diameter ; and hence in its leakage surface in contact with the insulation, more than compensates for the reduced radial thickness of the insulation.

The I. E E. standards for vulcanised rubber cables are 600 megohms grade up to 250 V and 2,500 megohms grade up to 650 V. The insulation of paper or fibre cables is much lower, and is from 70-110 megohm/mile in sizes of cables for which vulcanised rubber cables have actually their 'grade' values of insulation resistance. For India 300 megohm grade is not recommended. 600 megohm is the most satisfactory. Cables are put in coils of 110 yds. or 1/16 mile.

Insulating Materials for H. T. Cables :—

(*i*) Vulcanised bitumen cables have been used as distributors in mining and other industrial service. The bitumen suffers a surface attack by alkalies, although it is immune from attack of acids This softens the bitumen. It has been observed that the softening of bitumen by saponification is due to leakage current, moisture and heat ; and usually occurs on the negative main, since it is only there that alkali is produced electrolytically. The incorporation of 5-10 °/o of high-grade vulcanised rubber in vulcanised bitumen neutralises this effect.

(*ii*) Paper is mostly used for insulation of cables for pressures 3,000 V or higher. The paper has got good mechanical and electrical properties. Suitable paper stands heating in service, better than rubber ; also it is cheaper than rubber and has a higher or B. D. V., though its insulation resistance is low 70-100 megohm/mile in large sizes and 150-300 in smaller sizes Paper-insulated cables may be impregnated (under heat and vacuum) after the paper is applied or before being wound on the cable. Pure manilla paper, or paper containing wood pulp is used for insulating cables. Paper itself is very hygroscopic and it is important to protect all joints and ends during laying.

E. H. T. Cables :—The electrostatic strain on the insulation surrounding a charged conductor increases with the pressure to which the latter is charged and also increases with the curvature of the conductor, (*i.e.*, is greater for a small wire than for a large wire charged to the same pressure). The minimum permissible conductor radius in a high tension cable is $r = V/S$ cms , where $V=$ R. M. S. volt P. D., beetwen conductor and sheathing and $S=$maximum surface dielectric stress in R M.S. volt./c.m. This assumes the conductor to be circular. For stranded conductor a lead covering is put over the metal to make the outer surface smooth and cylindrical. If r, as required above, is $>$ than that required for conductivity and mechanical strength, the weight and cost of the conductor may be kept down by adopting a tubular section of internal radius r.

There is no difficulty in insulating cables for pressures up to 20,000 V between cores, and 3-core, 33,000-V cable is now a standard product.

Graded Insulation and Intersheaths for E. H. T. Cables :—Where a charged electrical conductor is surrounded by a uniform thickness of a homogeneous insulating material, the electrostatic stress on the latter is much more intense on the inner layers, adjacent to conductor, than on the outer layers ; and the inner layers of insulation may be broken down or deteriorated by overstrain. To obviate this, use successive layers of different insulating materials having different S.I.C. The complete insulation then forms concentric condensers in series and the distribution of the pressure is determined by S.I.C. of each layer.

Manufacturers confine the number of layers to 4. and then the stress, in spite of being distributed uniformly is distributed in steps. Another drawback of grading the insulation is that there is great difficulty in obtaining different insulating materials of suitable electrical and mechanical properties, which can be used in the first place and relied upon to preserve their properties unchanged, and not to attack each other chemically in the course of 20 or 30 years.

The intersheath method has been found more flexible and probably more reliable. This method consists in laying of the metallic sheathings from time to time during the application of insulation, which is itself of the same material throughout, and these concentric metal sheathing electrodes are 'anchored' at any desired potential. The potentials of the intersheaths may be fixed by condensers connected between them or by tapping connections from transformer or generator windings at suitable points, in the case of H.T.D.C. Thury system, by small natural or artificial leakage currents, tappings being taken from the connections of the series connected generators. The intersheaths themselves may be of lead or they may be of copper wire used for power transmission.

The conditions calling for grading (either by insulation or intersheathing) are (1) working pressures 7 60 K. V., (2) maximum stress 7 60 K. V./E. M., (3) where cable diameters without grading, would exceed, say, 3 in. For most practical purposes one intersheath will do. In the present state of practice such cables are required only for short distance interconnecting with E. H. T. transmission lines in city areas or round about power-houses railways, etc.

Earthing:—The need for keeping at earth potential all metal work not intended to be a part of electrical circuit is essential.

It can be taken as a universal practice that metallic sheathings of cables or metallic pipes, joint boxes, etc., containing cables should be earthed efficiently. An uncertain or 'floating' earth spells trouble for the future; because the development of a fault means a danger of electrical shock, a serious risk of fire, and a sure cause of electrolytic corrosion. The necessity for this efficient earthing of cable lead sheaths or armouring cannot be over-emphasised; and when it is carried, all possible precautions must be taken to maintain the efficiency of the earth already established.

When a stray current flows from a cable sheath into the earth it is only a matter of time before the sheath

is eaten through and the insulation exposed, a fault in the cable then following. This might easily occur at a number of places along a line of unearthed or inefficiently earthed sheath. This disconcerting peril of the trouble lies in the unpleasant fact that, by the time it is discovered, the damage is done and the length of the cable is probably ruined. The stray currents entering and leaving a buried cable sheath may not originate from the supply company's own network, but this does not lessen the necessity for the stated precaution being taken.

The usual method adopted in earthing the cable is that a brass strip about $\frac{1}{2}$ inch wide is wrapped round the leadsheath and kept tight by bolting, and then soldered to ensure a permanent contact. The ends of the strips are then bolted again to the wall of the C. T. joint box which, being unpolished, makes a good earth plate.

471. In Conductors Running Underground:—The following systems are generally used in *India* :—

Solid System :—Insulated cables without armour are laid in wood, stove earthen-wire or iron troughs filled up solid generally with bitumen, which is heated to fluid state before pouring in the trough and the filling in compound entirely surrounds the cable.

Insulated cables placed underground are used over distances up to as much as 10 miles. The voltages employed being from 6,000 to 13,000. For distances greater than this, higher voltages are desirable in order to economise in copper.

Great care should be taken to see that there is no air bubble in the trough. The cables rest at suitable intervals, say, 1′-6″ apart, on bridge pieces so that it does not touch the troughing below. Two or more cables may be laid in the same trough of sufficient section. The top is covered with brick or other suitable cover.

Bitumen should be filled in 3 or more operations to ensure the cables being entirely surrounded; also to avoid air spaces, which lend themselves to the collection of moisture; filling in to be done in dry weather and with a clearance between the cables if more than one cable is placed in a trough.

Where more than one cable is laid in one trench a spacing of 12 to 18 inches should be allowed in order to prevent mutual heating effect and also to ensure that a fault in one cable will not spread immediately to the others.

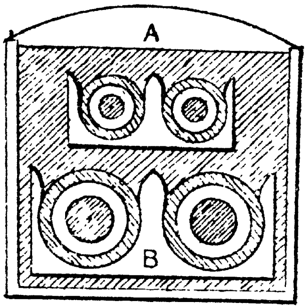


Fig. 8·17.

(2) *Direct System* :—In this, armoured cables are generally laid directly on the ground and covered with a creosoted wood plank or reinforced concrete slabs having no further protection. In soils free from sulphur it is done with great success. The cables are laid to a depth of 2 to 3 feet and each individual cable should be surrounded with at least 3 inches of soft earth well pounded. A line of bricks or lengths of creosoted boards, 1″ thick 6′ long with a margin of at least 1″ on each side, are laid directly over the cable, before the trenching is filled up; this protects the cable and gives indication to future excavators of the presence of the cables. Ground must not contain impurities such as ash, sewage, etc.

(3) *The Crompton Trench System* :—In this bare copper strips 1 to $1\frac{1}{2}$ inch wide and 1/9 to $\frac{1}{2}$ inch thick rest in notches on the top of porcelain or glass insulators which are supported by timber which is embedded in the sides of a cement-lined trench. The trench is covered with a layer of flagstone.

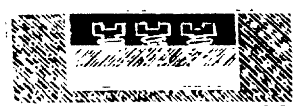


Fig. 8·18.

The insulators are spaced about 50 feet, and about every 300 feet a straining device is installed for taking up the sag in the conductors; hand-holes are located over each set of insulators

for cleaning and facility of inspection. The trench is given a proper slope and necessary outlets are kept to carry away all rain water to a proper drainage system.

The wire is so nearly horizontal throughout its entire length that the horizontal component of the tension, instead of the resultant, may be considered the tension acting at all points of the wire.

472. Erection of Aerial Conductors:—There are two considerations :—(1) The greatest possible tension in the conductor, which will occur at minimum temperature, must be less than the elastic limit of the conductor. (2) The wire is so nearly horizontal throughout its entire length that the horizontal component of its tension, instead of the resultant, may be considered the tension acting at all points of the wire.

(*a*) In general practice the tension is adjusted to one-fourth that of the breaking strain when the wire is shortened by the coldest weather. As the tension of the wire between two supports is such that the sag at the centre of the span is less than one-twentieth of the span, the curve formed by the wire may be taken to be a parabola and the tension of the wire is given by,

$$T=l^2 w/8d$$

where,

T=tension in kilogrammes,

l=the length of the span in metres,

d=the sag at the centre of the span also in metres,

w=weight of the wire in kilogrammes per metre,

or, $l=\sqrt{8d\ T_m/w}$, where

T_m=maximum safe tension of the wire in kilogrammes, *i.e.*, the tensile strength in kilogrammes divided by the factor of safety which is generally taken as 4.

When the sag is a small fractional part of the length of the span, the length of the wire is given by L where $L=l\ (1+8d^2/3l^2-32d^4/5l^4+etc)$. It is usual to omit all except the first two terms.

Hence, $L=l+8d^2/3l$ metres.

Let t denote the temperature at which the wire is erected, L and d the corresponding length of wire and

sag, respectively, and let L_1 and d_1 be their values at the minimum temperature t_1. The length of wire L at the time of erection is given by

$L=L_1 \{ 1+\alpha (t-t_1) \}$, where

α is the coefficient of linear expansion of the wire.

(b) In pound and foot unit

If l=length of span in feet,

D=dip or sag in feet at the lower temperature,

D_1=dip or sag in feet at higher temperature,

S=stress in lbs. at the lower temperature,

S_1=stress in lbs. at the higher temperature,

w=weight of wire in lbs. per foot,

P=wind pressure of wire in lbs. per foot.

The value of maximum wind pressure is 25 lbs. per square foot. Langley shows the pressure of wind normal to flat surfaces to be equal to $P=0\ 0036\ V^2 = V^2/280$, where P is the pressure in pounds per square foot and V is the velocity in miles per hour.

For round smooth wire $P=0{\cdot}002\ V^2$ (lb. per sq. ft.)
For bare concentric strands $P=0{\cdot}0025\ V^2$ (lb. per sq. ft.)

$W=\sqrt{w^2+P^2}$

T=difference between lower and the higher temperature.

K=coefficient of expansion
for copper$=0{\cdot}0000095$,
for aluminium$=0{\cdot}000013$.

Then $D=l^2 w/8S$

$D_1=\sqrt{D^2+l^2 \times (T\times 3/8K)}$

$S_1=S\times D/D_1$

The length of wire in span $=l+8D^2/3l$.

(c) With the supports at different levels the line forms a catenary, the lowest point of which is no longer midway between the supports, the curve can, however, be prolonged until it reaches a point which is at the same level as the higher support and the distance X_1 to the lower point of the catenary will be equal to half the assumed span S_1 and may be computed

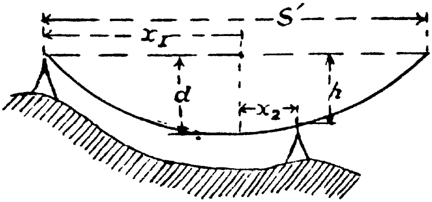


Fig. 8·19.

$X_1 = l_h/2 + ht/wl_h$ (ft.)

$X_1 = l_h\sqrt{d}/(\sqrt{d-h}+\sqrt{d})$

Where l_h is the horizontal distance between the supports.

d = the sag measured from the higher support,

t = the tension in the wire in lbs. at the higher support,

w = weight in pounds per unit length,

h = the difference in height of supports.

The sag d may be computed as $d = d_1\,(1+h/4d_1)^2$

Where d_1 is the sag as determined for the same span l and the same loading and is $= l^2 w/8S$

Also $X_2 = l_h/2(1-h/4d_1)$

Example 17. An aerial transmission line, in which the poles are spaced 150 feet apart, is constructed of No. 4/0 S.W.G copper wire. If the minimum temperature be 0° C. and that when the wires are erected 55° C., determine the tension to which the wires can be adjusted and the sag at the time of erection.

Solution :—

No. 4/0 S.W.G. wire weights 0·721 kilogrammes per metre Tensile strength of hard-drawn copper wire = 3500 kilogrammes per sq. cm. So that allowing for a factor of safety of 4 the safe tension of the wire at mm. temp. = 3,500/4 = 875 kilogrammes per sq. cm. Now No. 4/0 S.W.G. has a cross-sectional area of 0·8128 sq. cm. So that the maximum safe tension of the wire = T_m = 875 × 0·8128 = 711·2 kilogrammes.

150 feet = 150 × 0·30480 metres = 45·72 metres.

The sag at the centre of span at 0°C. $=d_1=l^2w/8T_m$.

$$\therefore d_1=\frac{45{\cdot}72^2\times0{\cdot}721}{8\times711{\cdot}2}=0{\cdot}2024 \text{ metre.}$$

Length of the wire in span at 0°C.

$=L_1=l+8\,d_1^2/3l=45{\cdot}72+8\times0{\cdot}2024^2/3\times45{\cdot}72$

$=45{\cdot}72$ metres, nearly.

Since the coefficient of linear expansion of copper is 0·0000168 per degree centigrade, the length of wire at 55°C.

$=L=45{\cdot}72\ (1+{\cdot}0000168\times55)=45{\cdot}72\times1{\cdot}00092$

$=45{\cdot}762$ metres.

Substituting this value of L in the equation

$$L=l+8d^2/3l$$

The sag at the time of erection $=d$

$$=\sqrt{\frac{0{\cdot}042\times3\times45{\cdot}72}{8}}=0{\cdot}85 \text{ metre}=\text{say, } 2'\text{-}10''$$

Substitute this in equation $T_m=l^2w/8d$. The tension of wire at the time of erection has to be adjusted to $T_m=45{\cdot}72^2\times0{\cdot}721/8\times0{\cdot}85=221{\cdot}6$ kilogrammes.

473. Temperature Rise of Overhead Conductors :—The sag in the line is affected by the rise of temperature of the conductor. For a solid copper conductor in still air the temperature rise is approximately given by—

$$t=19{\cdot}5\ \rho\ I^2/(d^3\times10^6)\ ;$$

where t=temperature rise, in °C. ; ρ=specific resistance of hard-drawn copper in microhms per cm. cube, at temperature $(t+t_a)$ °C., t_a being the air temperature, in °C.; I=current, in amperes ; d=diameter of conductor, in inches.

Now, the appropriate value of ρ cannot be determined without knowing t. It is necessary, therefore, to assume a limiting temperature $(t+t_a)$, and calculate t from the formula. If the difference between the former and the latter is not approximately equal to the actual air temperature, the calculation should be repeated with a different assumed value for $(t+t_a)$.

The current corresponding to a given temperature rise at the above-stated atmospheric temperature can be calculated directly from the inverted formula: $I = \sqrt{(td^3 \times 10^6/19{\cdot}80)}$. For stranded conductors the diameter of equal copper section should be taken for d in the above formula; the current for stated temperature rise will be about 8 % greater than that calculated from the formula.

The temperature rise in steel-cored and aluminium cables is less than in copper conductors of equal resistance, because the radiating surface in the former is greater than in the latter.

It should be noted, however, that the size of conductors for overhead lines to be determined generally by considerations of power or voltage drop and not by temperature rise.

474. Spacing of Conductors:—The spacing of conductors should be such that the wires cannot swing within arcing distance of one another in the span. Short spans at low pressures should have the wires at least 1′-6″ apart and the distance must be increased with the pressure and the dip. Up to 10,000 volts, with short spans 2′-6″ is sufficient.

In long spans the wires should be arranged so that no two are in the same horizontal plane, because of their liability to blow together in a wind. For pressures over 20,000 volts the minimum distance in inches would be $6 + 0{\cdot}00125 \times$ volts.

The conductors of every aerial line, erected in over, along and across any street or part of a street shall be attached to support at intervals not exceeding 220 feet.

475. Corona:—It is due to the breakdown in the insulation of the air near the conductor. The loss due to corona can be measured by a wattmeter.

Let E_v = effective kilovolts from phase wire to neutral at which corona becomes visible.

$M_v = M_o = 1$ to $0{\cdot}93$ for wires, the higher value applying to a polished wire. $M_v = 0{\cdot}72$, local corona all along conductor and $0{\cdot}82$, decided corona all along conductor for 7-strand cable.

$G_0 = 21 \cdot 1$ kv. per cm. being the dielectric strength of air at 25°C. and 76 cm. pressure.

δ = air density factor $= 3 \cdot 92 b / (273 + t)$
$= 1$ at 76 cm. pressure and 25° C.

b = barometric pressure in cm.

t = temp., degree centigrade.

r = radius of conductor in cm.

S = distance between the centres of conductors in cm.

$log_e = 2 \cdot 303 \; log_{10}$.

P = power per kilometre wire, kilowatts.

$k = 344$.

f = frequency, cycles per second.

e = effective kilovolts to neutral of conductors.

M_0 = irregularity factor of conductor.
= 1, for polished wire, 0·98 to 0·93 for roughened or weathered wires, and 0·87 to 0·83 for seven-strand cable.

e_0 = disruptive critical voltage to neutral and is always lower than E_v.

Then, $E_v = M_v \, G_0 \, \delta \, r \left(1 + \dfrac{0 \cdot 301}{\sqrt{\delta r}}\right) log_e \, S/r$ kv. to neutral ;

$P = (k/\delta) \, f \sqrt{r/S} \, (e - e_0)^2 \, 10^{-5}$ (per kilometre of single conductor)

where, $e_0 = G_0 \, M_0 \, r \, \delta \, log_e \, S/r$

To obtain kilowatt per mile, multiply by 1·61.

Corona limits of voltage.—Kilovolts between lines (three-phase at sea-level).

$e_0 = \sqrt{3} \, G_0 \, M_0 \, r \, \delta \, log_e \, S/r$, where $M_0 = 0 \cdot 87$.

Corona loss can also be determined from the following equations :—

(1) Corona loss $= (e - e_0)^2 \times$ constant (K) watts per kilometre of conductor and voltage in maximum kilovolts to neutral.

(2) $e_0 = 29 \, r \, log_e \, (S/r)$ for round conductors.

(3) Constant $K = 2 \cdot 4 \, (f + 25) \sqrt{r/S}$

Example 18.—Calculate the corona loss on a monophase transmission line 50 km. long with 00 S.W.G.

conductors placed 120 cm. apart and operated at 110 kilovolts 50 cycles per second at (1) normal air density, (2) for storm conditions when the critical voltage e_0 is lowered to 80 per cent. of its fair weather value.

Solution :—

$e_0 = 29\ r\ log_e\ (S/r)$
$e_0 = 29 \times 0{\cdot}442 \times 2{\cdot}303\ log_{10}\ (120/0{\cdot}442)$
$= 12{\cdot}82 \times 5{\cdot}6 = 71{\cdot}8$ kilovolts (max.) to neutral
$= 68\ 2$ kilovolts to neutral.

Allowing 5 per cent. for roughness of wire

The constant $= 2{\cdot}4 \times (f + 25)\sqrt{r/S}$
$= 2{\cdot}4\ (50 + 25)\ (\sqrt{0{\cdot}442/120})$
$= 11.$

110 kv between lines $= 78$ kv. max. to neutral.
$\therefore$ loss $= 11\ (78 - 68{\cdot}2)^2$ watts per km. of conductor
$= 1{\cdot}05$ kW. per km. of conductor
$= 105$ kW. for the whole line.

For storms :—

$V_0 = 68{\cdot}2 \times 0\ 8 = 54{\cdot}6$ kv. (max.)
$\therefore$ loss $= 11 \times (78 - 54\ 6)^2$ watts per km. of conductor,
$= 11 \times (23\ 4)^2$ watts per km. of conductor,
$= 6\ 02$ kW. per km of conductor,
$= 602$ kW. in the whole line.

Example 19.—A three-phase line 100 miles long, size of conductor 2/0 S.W.G. copper; E.M.F. 100 kv. frequency 50 cycles, spacing 10 feet. Temperature 20°C., 76 cm. barometric pressure, and a co-efficient of roughness $M_0 = 0{\cdot}95$. Determine the total corona loss.

Solution :—

$\delta = (3{\cdot}92 \times 76)/(2{\cdot}73 + 20) = 1{\cdot}01$
Diameter of 2/0 wire $= 0{\cdot}884$ cm.
$r = 0{\cdot}442$ cm.
$S = 10 \times 12 \times 2{\cdot}54 = 305$ cm.
$e = 100/\sqrt{3} = 57{\cdot}7$ kv. to neutral
$G_0 = 21{\cdot}1$ kv.
$log\ 305/0{\cdot}442 = 2{\cdot}84$

$P=(k/\delta)\, f\sqrt{r/S}\,(e-e_0)^2\, 10^{-5}$ kW. per kilometre of single conductor.

$= (344/1{\cdot}01) \times 50 \times \sqrt{\cdot442/305} \times [57{\cdot}7 - (21{\cdot}1 \times 0{\cdot}95 \times 0{\cdot}442 \times 1{\cdot}01 \times 2{\cdot}303 \times 2{\cdot}84)]^2 \times 1{\cdot}61 \times 10^{-5}$ kW. per mile per wire.

$= 340{\cdot}6 \times 50 \times 0{\cdot}039\ (57{\cdot}7 - 58{\cdot}5)^2 \times 1{\cdot}61 \times 10^{-5}$

$= 0{\cdot}007$

Total corona loss$=0{\cdot}007 \times 100 \times 3 = 2{\cdot}1$ kW.

Note that smoke, fog, sleet, rain and snow, all lower the critical and visual voltages and increase the corona losses. Local brushes cause deterioration of conductors by ozone and nitric acid formation specially at the point of support.

In practice, it is generally not advisable to operate at a higher voltage than that corresponding to e_0, otherwise the loss would become very high during wet weather or when the conductor surface becomes roughened.

The various factors affecting the potential difference at which corona starts are briefly (1) air density, the effect varying inversely as the density, (2) state of surface heat and other factors as represented in the equation.

476. The Unit Thermal Resistance is the resistance of a path through which the difference of temperature of 1°C produces a heat flow of one joule per second. This is called a **thermal ohm.**

To find the temperature rise of a buried cable :—

Let θ=temperature rise of conductors in degrees C.

H=heat developed in conductors in watts.

S=thermal resistance between conductors and outer surface of cables in thermal ohms.

G=thermal resistance of ground surrounding the cable.

Suppose a value of temperature rise is selected corresponding to the maximum permissible operating temperature of the dielectric, and if

I=the current loading per conductor,

n=number of conductors,

R_θ = resistance of conductor in ohms at working temperature corresponding to the temperature rise θ, then $H = n\, I^2\, R_\theta$;

$\theta = H\,(S+G)$;

or $I = \sqrt{\theta / n\, R_\theta\,(S+G)}$

i e, the current-carrying capacity as determined by the temperature rise—Ohm's Law for heat.

To determine the thermal resistance between conductor and sheath, take one cm. length of the cable with diameter as

$dS = \dfrac{K\,dx}{2\,\pi\,x}$, where dx is the thickness,

$2\,\pi\,x$ = area and
K = the thermal resistance in thermal ohms.

$$S = \frac{K}{2\,\pi} \int_r^R \frac{dx}{x} = \frac{K}{2\,\pi}\ \log_e \frac{R}{r} \text{ thermal ohms per cm.}$$

Example 20.—20,000 K.V A. (16,000 kW. at 80 °/o power factor lagging) at 50 cycles and load factor 50 °/o, to be transmitted a distance of 15 miles by means of a three-core cable. Voltage at the receiving end is 22,000, value of dielectric power factor 1 °/o. Determine (1) the total annual I^2R loss, (2) total annual dielectric loss in the cable.

Solution :—

The line current corresponding to maximum load

$$= \frac{20{,}000 \times 1{,}000}{\sqrt{3} \times 22{,}000} = 525 \text{ amperes.}$$

As the load factor is 50 °/o the R.M.S. current flowing in each conductor is $I = 525 \times 0{\cdot}5 \times 1{\cdot}20 = 313$ amps.

This is the current flowing at the receiving end of the line and at the sending end it will be usually smaller owing to the effect of the charging current.

Taking the mean value of the current, the actual loss is approximately.

$$\sqrt{(I\ cos\ \theta_r)^2 + (I\ sin\ \theta_r - I_c)^2}$$

where, I_c = the current taken by a condenser having a capacitance one-half that current taken by a conductor, shunted between the conductor and neutral at the receiving end of the line.

The line I^2R losses may be determined by multiplying the losses which would be produced by the load current by the reduction factor.

$$K = \{(I\ cos\ \theta_r)^2 + (I\ sin\ \theta_r - I_c)^2\}/I^2$$

The case of 22,000 volts, 0·25 sq. in. cable (capacitance 0·4 microfarads and resistance 0·178 ohms per mile at 20° C).

$$\text{Now } I_c = 2\pi f \frac{C_0}{2}\ El.$$

$$\therefore \quad I_c = 2\pi \times 50 \times 0·20 \times 10^{-6} \times \frac{22,000}{\sqrt{3}} \times 15$$

$$= 11·97 \text{ amperes}$$

$$\text{and } K = \frac{(313 \times 0·8)^2 - (313 \times 0·6 - 11·97)^2}{(313)^2} = 0·955$$

Hence, the total I^2R losses in the cable per annum

$$= \frac{313 \times 313 \times 0·178 \times 15 \times 3 \times 8,760 \text{ (hours)} \times 0·955}{1,000}$$

$$= 6,564,908·37 \text{ kW.-h.}$$

and annual total dielectric losses

$$\frac{2\pi \times 50 \times 0·4 \times 10^{-6} \times 22,000 \times 22,000 \times 15 \times 3 \times 8,760}{1,000 \times 100 \times \sqrt{3}\ \sqrt{3}}$$

$$= 79,951·27 \text{ kW.-h}$$

477. Ferranti Effect :—The voltage at the receiving end in a long-distance transmission line open-circuited or very slightly loaded is greater than that at the sending end. This is known as *ferranti effect*. This rise of pressure is due to the E.M.F. of self-inductance of

the charging current being in phase with the impressed voltage at the sending end of the line Both capacitance and inductance must be present to produce this phenomenon In such cases the reactance is fairly large in comparison with resistance.

The load current with lagging or unity power factor in the receiving circuit is to produce a voltage at the receiving end lower than that impressed on the line at the sending end. But the effect of charging current is to raise the voltage at the receiving end.

To determine the magnitude of the rise of pressure one-half of the total line capacitance will be assumed to be concentrated at the receiving end.

The charging current I_c flowing in the conductor =

$$2 \pi f \frac{C_o}{2} E l.$$

Let C_o =capacitance per mile of conductor in farads.
l=length of line in miles.

The induced volts are $I_c X = 2 \pi f \; L_o I_c l$.

Substituting I_c

$$I_c X = (2 \pi f)^2 \frac{L_o C_o}{2} l^2 E \text{ volts.}$$

The product of $L_o C_o$ for overhead lines is 3×10^{-11} approximately.

Hence the pressure rise at the end of the line

$$I_c X = (2 \pi f)^2 \frac{3 \times 10^{-11}}{2} l^2 E \text{ volts}$$

$$= 5{\cdot}9 \; E f^2 \; l^2 \; 10^{-10} \text{ volts.}$$

for 50-cycle lines this is $1{\cdot}5 \; E\left(\frac{l}{1{,}000}\right)^2$ volts,

Determine the power loss in the line due to the charging current :—

Let l be the length of the line, I_c = the charging current.

Supposing the voltage equality along the line, the actual value of the charging current will decrease

uniformly from its maximum value at the sending end to zero value at its receiving end.

The current at any point X miles from the sending end is $\frac{I_c}{l}(l - X)$.

The average value of the square of this quantity is

$$\frac{1}{l}\int_0^1 \frac{I_c^2}{l^2}(l-X)^2\,dX = \frac{I_c^2}{l^3}\int_0^1 (l-X)^2\,dX = \frac{I_c^2}{3}.$$

Hence, at open circuit the power losses in each conductor is $\frac{I_c^2}{3}R$.

478. Mixed Sending and Receiving End Conditions :—For some fixed conditions of sending and receiving stations such as when the voltage at the sending station and the power factor and power at the receiving stations are fixed. Mr. Bancarel has given the following method, which is very suitable for solution of such cases :—

$$E_r \cos\theta_r + RI = E_s \cos\theta_s \quad \ldots \quad \ldots \quad (1)$$

$$E_r \sin\theta_r + XI = E_s \sin\theta_s \quad \ldots \quad \ldots \quad (2)$$

also $E_r \cos\theta_r \times RI = 1{,}000\ PR \quad \ldots \quad \ldots \quad (3)$

$$E_r \sin\theta_r \times XI = 1{,}000\ QX \quad \ldots \quad \ldots \quad (4)$$

where P=power in kilowatt per phase delivered at the receiving end of the line.

Q=the reactive K. V. A. per phase delivered at the receiving end of the line.

Square equations (1) and (2) and add—

$$\therefore\ E_r^2 + 2RIE_r \cos\theta_r + 2\,XIE_r \sin\theta_r + (R^2+X^2)I^2 = E_s^2.$$

Whence by substituting for the second and third terms from equations Nos. (3) and (4).

$$E_r^2 + 2{,}000\ (PR+QX) + (R^2+X^2)\ I^2 = E_s^2$$

Substituting $\frac{1{,}000P}{E_r \cos\theta_r} = I$ and

multiplying throughout by E_r^2, we get

$$E_r^2\,E_s^2 - \left[E_r^4 - 2{,}000\,(PR+QX)\,E_r^2 + (R^2+X^2) \left(\frac{1{,}000P}{\cos\theta_r}\right)^2 \right] = 0 \quad \ldots \quad \ldots \quad \ldots \quad (5)$$

Let $S = E_s^2 - 2{,}000\,(PR+QX)$

Let $T = (R^2+X^2)\,\left(\frac{1{,}000P}{\cos\theta_r}\right)^2$

Thus (5) can be stated as $E_r^4 - SE_r^2 + T = 0$

whence $E_r = \sqrt{\frac{S \pm \sqrt{S^2-4T}}{2}}$

The solution giving the higher *value of E_r and consequently higher transmission efficiency is the one required in practice. Thus the + sign should be taken.*

Example 21.—Determine the voltage at the receiving end, the sending end power factor and current in a three-phase transmission line, 15 miles long, consisting of three hard-drawn copper wires No. 00 S.W.G. spaced at thirty inch delta.

Temperature 15°C. Load at receiving end 2,000 K.V.A. (1,600 kW. at 80 °/ₒ power factor lagging). voltage at sending end 11,000 volts, 50 cycles.

Solution :—

Resistance of each conductor is

$R = 0{\cdot}444 \times 15 = 6{\cdot}66$ ohms.

The inductance of each conductor is

$$L\ (0{\cdot}080 + 741\ \log_{10} \frac{30}{0{\cdot}174})\ 10^{-3} \times 15$$

And the reactance is

$X = 2\pi \times 50 \times 0{\cdot}0261 = 8{\cdot}2$ ohms.

$$P = \frac{1{,}600}{3} = 533 \text{ kW.}$$

$$Q = P \tan \theta_r = 533 \times 0{\cdot}75.$$
$$= 400 \text{ K.V.A. per phase.}$$
$$Cos\ \theta_r = 80\ \% \text{ lagging.}$$
$$E = \frac{11{,}000}{\sqrt{3}} = 6{,}351 \text{ volts to neutral.}$$
$$\therefore S = E_s^2 + 2{,}000\ (PR + QX)$$
$$= 6{,}351^2 - 2{,}000\ (533 \times 6{\cdot}66 + 400 \times 8{\cdot}2) = 26{,}675{,}641$$
$$T = (R^2 + X^2)\left(\frac{1{,}000\ P}{Cos\ \theta_r}\right)^2 = (6{\cdot}66^2 + 8{\cdot}2^2)\left(\frac{5{\cdot}33 \times 10^5}{0{\cdot}8}\right)^2$$
$$= 111{\cdot}6 \times 44{,}3889{,}062{,}500 = 4953{,}8019{,}375{,}000$$

The receiving end voltage E_r =

$$\frac{\sqrt{SX \pm \sqrt{S^2 - 4T}}}{2} = 4{,}900 \text{ volts to neutral.}$$

and the current $I = \dfrac{533 \times 1{,}000}{4{,}900} = 108{\cdot}77$ amps.

The sending end power factor =

$$\frac{E_r \cos \theta_r + RI}{E_s} = \frac{4{,}900 \times 0{\cdot}8 + 6{\cdot}66 \times 108{\cdot}77}{6{,}351}$$
$$= 73\ \% \text{ lagging.}$$

Example 22.—Determine the characteristics of the load at the sending station of a three-phase line 35 miles long, spaced in a four-foot delta. Temperature taken as 15°C. Load conditions at the receiving end are taken to be 10,000 K. V. A (8,000 kW. at 80 % power factor lagging), 40,000 volts 50 cycles ; transmission loss to be approximately 10 %.

K. V. A = 10,000/3 = 3,333 K. V. A. per phase.
kW. = 8,000/3 = 2,667 kW. per phase.

$$E_r = \frac{40{,}000}{\sqrt{3}} = 23{,}104 \text{ volts to neutral.}$$

$$Cos\ \theta_r = 80\ \% \text{ lagging.}$$
$$I = \frac{3{,}333 \times 10^3}{23{,}104} = 144 \text{ amperes.}$$

The transmission loss is 10 %. Hence, the resistance of each conductor will be $\dfrac{W}{I^2} = \dfrac{2{,}667 \times 10^3}{10 \times (144)}$

$$= 12{\cdot}37 \text{ ohms} = 0{\cdot}3534 \text{ ohms per mile.}$$

From the table we find the wire having the nearest resistance per mile is 0·334 ohm No. ·0000 S. W. G. having diameter of 0·400 inch.

The resistance of each conductor is 0·334 × 35 = 11·69 ohms.

The inductance of each conductor is

$$L = \left(0{\cdot}080 + 0{\cdot}741\, log_{10}\ \frac{48}{0{\cdot}2}\right)10^{-3} \times 35$$

$$= 1{,}245{\cdot}5 \times 10^{\ 6} \times 35 = 0{\cdot}0436 \text{ henry.}$$

The reactance is $X = 2\pi \times 50 \times L = 13{\cdot}677$ ohms

Thus $IR = 144 \times 11{\cdot}69 = 1{,}683{\cdot}36$ volts resistance drop.

$IX = 144 \times 13{\cdot}677 = 1{,}917{\cdot}5$ volts reactance drop.

The sending end voltage $Es =$

$$\sqrt{(E_r \cos\theta_r + IR)^2 + (E_r \sin\theta_r + IX)^2}$$

$$= E_r \sqrt{\left(\cos\theta_r + \frac{IR}{E_s}\right)^2 \left(\sin\theta_r + \frac{IX}{E_r}\right)}$$

$$E_s = 23{,}104 \sqrt{\left(0{\cdot}8 + \frac{1{,}683{\cdot}36}{23{,}104}\right)^2 \left(+0{\cdot}6 + \frac{1{,}917{\cdot}5}{23{,}104}\right)^2}$$

$$= 25{,}590 \text{ volts.}$$

Sending end phase angle is

$$Sin\ \theta_r - \frac{IX}{E_r}$$

$$\theta_s = tan^{-1} \frac{E_r}{Cos\ \theta_r - \frac{IR}{E_r}} = tan^{-1} \frac{0{\cdot}7621}{0\ 683} = 58^\circ - 30$$

or $cos\ \theta_r = 0{\cdot}5225$ lagging.

$$\therefore \text{ Loss} = \frac{(144^{\ 2} \times 11{\cdot}69}{1000} = 242\ 32 \text{ kW.}$$

$$\text{Efficiency} = \frac{2{,}667 - 242{\cdot}32}{2{,}667} \times 100\ \% = 91\ \%$$

Regulation =2,486 volts.

$$\text{Per cent. regulation} = \frac{25{,}590-23{,}104}{23{,}104} = 10{\cdot}7\ \%.$$

479. Insulation of Overhead Lines :—

(*a*) *Factors involved in insulator design* :—Insulators are required to stand both mechanical and electrical stresses, in addition to which the surface leakage path must have sufficiently high resistance to prevent any appreciable current flowing to earth. Electrical breakdown may occur either by flash-over or puncture. In a flash-over, an arc occurs between the line conductor and earth, (the latter being represented by the supporting pin of the insulator), and the discharge jumps across the air-gap in its path. In a puncture, the discharge occurs from conductor to pin through the body of the insulator. When a breakdown of the former type is involved, the insulator will continue to act in its proper capacity after the event unless fractured by the heat of the arc, but after a puncture it is permanently injured. It is thus of importance to provide sufficient thickness of porcelain in the insulator to resist puncture by the combined effect of the line voltage and any probable transient pressure rises on the line. The ratio of puncture strength to flash-over voltage may be termed the factor of safety of the insulator against puncture, and this ratio should be high so that a good margin is obtained to protect the insulator from complete failure.

Porcelain is commonly used in the manufacture of insulators. The dielectric strength of porcelain is of the order of 9,000 volts per mm. of thickness ; defective vetrification of the interior may result in a lower puncture voltage than the calculated value. The dielectric strength is very much dependent upon the temperature. It commences to decrease rapidly at about 75°C. and at 250°C. it practically ceases to be an insulator. The ohmic resistance of porcelain at normal temperature is about 2×10^{12} megohms per cent. cube. Both the dielectric strength and the ohmic resistance are dependent upon the nature of the porcelain and these may differ substantially when in use.

(*b*) *Insulator tests* :—There are two separate classes of tests employed in practice ; the one is the *type test* and the other the *routine test.*

The TYPE TESTS made on a specimen insulator are as follows :—

(1) Successive immersion in hot and cold water.

(2) A dry flash-over test in which the insulator is mounted as nearly as possible in accordance with the condition of practical operation, and subjected to a gradual increasing voltage until the flash-over occurs.

(3) A repetition of (2) while the insulator is subjected to artificial rain, delivered in a downward direction, usually at an angle of 45°.

(4) A puncture test in which the whole insulator with its fittings is completely immersed in oil and the voltage again raised until puncture occurs.

(5) A mechanical test, in which loads of the same nature, as will occur in practic are applied and increased until failure.

(6) A porosity tests in which broken pieces are subjected to fuschine dye under pressure.

These tests are applied to only a specimen insulator of the same form and the results are the representative of the type of insulators.

The ROUTINE TEST is applied to every insulator and consists of " proof load test " and " high voltage test." In the former the insulator is subjected to a mechanical load exceeding by a fixed percentage of the maximum working load. In the latter test the insulator is inverted and filled with water, and a voltage which just sparks over is applied and maintained for five minutes without puncturing it.

(*c*) *Pin type insulators.*—The economic limit is about 66,000 volts. They may be made for all voltages up to 800 volts, but, for the high voltages, the weight and size increase very rapidly, and the cost becomes excessive. Increase of voltage involves the complete replacement of all the insulators.

(*d*) *Suspension Insulators.*—These are used for all voltages over 66,000, and in some cases they are used on lines of as low voltage as 33,000 volts.

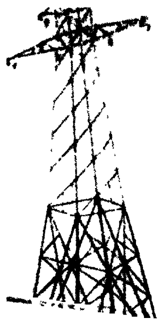
Advantages.—(1) Lower cost for high voltage.

(2) The use of a string to which units can readily be added and thus the voltage of the line may be raised as soon as the load demand makes this desirable

(3) With a suspension string, greater flexibility reduces the risk of mechanical failure.

(4) If one is damaged, the remaining units will be sufficient to keep the line in operation until replacement can be made.

(5) The insulator hangs below the cross-arm, and is, to some extent, shielded by it. This may add to the security against atmospheric disturbances and there is less risk of earthing due to built-up snow or to birds.



Suspension Insulators Shown in Position.
Fig. 8·20.

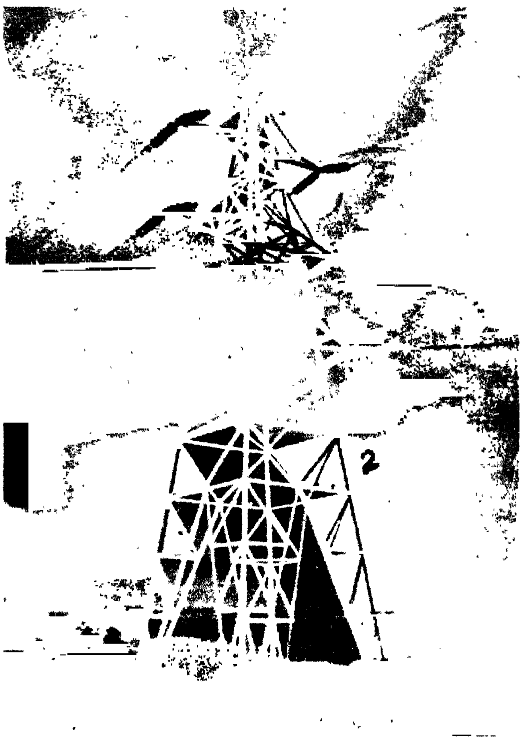
Disadvantages.—(1) They require higher supports and the absence of rigidity necessitates greater clearances.

(2) With unequal span lengths, or with supports on different levels, difficulty also arises owing to the tendency for the insulator string to depart from the vertical.

(*e*) *Tension Insulators.*—These insulators are used at anchor supports or at dead-end points, and they must be

able to withstand the full longitudinal tension in the conductors, and, at the same time, must be suitable for operation in a horizontal position.

If the ultimate strength is very high, either a specially-designed insulator string or two or more stranded strings are used in parallel. The use of double or treble string of insulators is expensive.



Tension Insulators.

Fig. 8'21.

(f) Arcing Horns and Rings.--These are used to prevent the porcelain from damage by the arc produced by the high-potential discharge. One of the horns or rings is connected to the power line and the other is earthed. The arrangement is such that the arc is taken up by the horns or rings without creating any damage to the insulators by the heat of the arc In the ring-design the arc may lie anywhere around the insulator according to the direction of the wind.

Application of these devices decreases the flash-over voltage, but the disadvantage is counterbalanced by the protective value of the equipment.

(*g*) *High-frequency Effects.*—The electrical stresses produced by high-frequency potentials are totally different from those produced by the potentials at odinary-line frequency. The insulators allow a leakage path to these high-frequency currents, and the insulators, which stand the flash-over test at line frequency, sometimes fail due to atmospheric disturbances The other reason for this is that the corona has no time to form and relieve the stress by the rupture of the air.

Therefore, to prevent puncture at high-frequency disturbances, the ratio of the flash-over voltage to puncture voltage should be low.

In an oscillation, the energy passes from one form to the other, so that assuming no loss, $\frac{1}{2}\,Li^2 = \frac{1}{2}\,Ce^2$

or, $e/i = \sqrt{L/C}$ ....(1)

The term $\sqrt{L/C}$ is called natural impedance of the line.

From equation (1), the maximum voltage produced on interruption of the current I is $e = I\sqrt{L/C}$ ....(2)

This rise of voltage limits the current that may safely be interrupted, and renders a short circuit dangerous.

Any sudden change in load will alter e and i, and as the energy of electro-static and magnetic field cannot change in zero time, e and i must necessarily pass through some transient values before the steady state is reached.

The time involved in reaching the steady state depends upon the resistance in the circuit which dissipates the changing energy in the form of heat or, taking in a wide sense, hysteresis and dielectric losses in the fields themselves or, an arc formed breaking down the insulation of the system If this r, the resistance, is equal to, or greater than, $\sqrt{L/C}$, the transient is non-oscillatory or quickly dies out. If r is less than $\sqrt{L/C}$, the transient is oscillatory.

(*h*) *Factor of Safety of Insulators.*—Insulators should have the same mechanical factor of safety as the wires which they support, that is, 5 according to B. O. T. The breaking load of a terminal insulator is the same as that of the wire with which it is used. When a large solid copper wire makes a considerable angle as at a corner pole, it is advisable to break up the angle by using two insulators, otherwise there is a considerable danger of breakage occurring.

(*i*) *Breaking Stress of Round Insulator Pines.*—

W = elastic limit for wrought-iron or steel.
L = length in inches above cross-arm.
D = diameter of pin in inches.
C = coefficient of rupture.

Then,

$$W = \frac{C \times 525\ (D/2)^3}{L};$$ a factor of safety of 2 or 4 should be allowed.

C for mild steel 100 to 120, where breaking stress =70.000 to 80,000 lbs./□″.

The elastic limit of steel pins is about 80 per cent. of breaking stress :

480. Causes of Insulator Failure :—The following are the chief causes for the insulator failure.

1. *Deterioration by Cracking of the Insulators.*—The insulators deteriorate after a certain period of service. This is due to alternate and varying application of heat and cold, which cause expansion and contraction of the porcelain, steel and the binding material. These produce such stresses as to crack the insulators. This can be avoided by giving a cushion of lead thimbles or tarred humped wrappings between the insulators and the steel pins.

2. *Porosity.*—This is due to underfiring of the insulators. The moisture penetrates the insulators and decreases the insulating resistance which causes the leakage current to pass through the insulators and heat them up. This ultimately causes complete failure of the insulators.

3. *Puncture of Weak Porcelain.*—This will be due to improperly vitrified material in the insulators and can be avoided by applying severe routine tests during the course of manufacture.

4 *Shattering by Power Arcs.*—This is caused by the formation of power arcs due to high-frequency effects and can be minimised by arcing horns and rings.

5 *Flash-over Caused by Dust Deposits.*—The dust, salt or soot deposits cause flash-over troubles at local sections of the transmission lines. These substances decrease the flash-over voltage, when wet. This trouble can be minimised by employing bigger insulators at such sections and also periodically cleaning them.

6. *Failure from Mechanical Stresses.*—This trouble cannot arise if the insulators stand the routine mechanical test.

7. *Short-circuiting by Birds and Similar Objects.*—Large birds create short circuiting. This is got rid of by increasing the spacing of the conductors or using suspension insulators.

481. Factors Governing the Design of Line Supporting Structures:

(*a*) *Rigidity of Supports*—The line supports have to withstand the vertical load of the line as the horizontal tensions of a line on a tower are equal and opposite and cancel each other. This allows flexible poles to be used, which are mechanically stronger for transverse and vertical loads. The disadvantage of these poles is that a breakage in one span will cause failure of a number of poles one behind the other. For this reason extremely flexible poles are not used in practice. The British regulation specifies that *the strength of a pole in the longitudinal direction must not be less than one-fourth of that in the transverse direction.*

The wooden poles are extremely flexible. There is a form of narrow base steel poles, which are also flexible. To prevent these poles from failure or swinging by wind-pressure, anchor supports are used at some poles.

The flexible poles are only useful for short spans and for short transmission lines. For longer spans it becomes impracticable to use flexible poles and rigid poles are invariably used.

(*b*) *Wind Load.*—The wind load on a plate is given by $P = KV,^2$ where P is the pressure in pounds per square foot, V the velocity in miles per hour, and K, a constant depending on the condition of the air. As given by Newton, the value of K at sea-level and zero temperature is 0·0027. This value is a bit smaller than the actual value, as there is a partial vacumn created behind the plate, and value ranging from 0·003 to 0 002 is adopted in practice.

The wind-pressure on a cylindrical surface of diameter D is less than that on a plane surface of width D and of equal length, and for practical purposes the pressure on a cylindrical surface is taken to be 0·5 to 0·7 times PDL, where D is the pressure per square foot on a plane surface, D is the diameter of the cylinder and L is the length.

The value of K remains constant for a constant product VD, but it varies for different values of VD. If the product lies between 15 and 40 (V in M. P H. and D in inches), the value of K varies from 0·00295 to 0·00304. Hence, over this range the wind-pressure in pounds per square foot of the projected area can be taken as 0·0030 V^2. Thus, if the formula $P = 0{\cdot}0040\,V^2$ is accepted for flat surfaces, the pressure on a cylindrical surface will be 75 per cent. of the pressure on a flat surface of equal projected area. The British regulation for wind-pressure on transmission lines is 8 lbs. per sq ft., it being assumed to correspond with the velocity of 50 M. P. H. The value obtained for K from this is 0·0032.

(*c*) *Ice Loading.*—Under some temperature conditions ice deposits on the line wires. This deposit is not necessarily uniform throughout the length of the line. The weight of the deposit varies with the size of the conductor, and it is common practice to assume that the total load will be equivalent to the weight of a cylinder of ice of constant radial thickness. In

British Regulations the thickness of ice is taken as $\frac{1}{2}$ inch for high-tension lines and as $\frac{1}{4}$ inch for low-tension distribution lines, the latter being assumed to be less subject to ice accumulations owing to their more sheltered location. The assumption of a constant radial thickness of ice is equivalent to the assumption that the weight of the coating will be directly proportional to the diameter of the conductor, and assuming the weight of ice per cubic inch is 0·033 lb.; the weight of ice per foot becomes $0·623\,D+0·312$ for $\frac{1}{2}$ inch radial thickness, or $0·311\,D+0·078$ of $\frac{1}{4}$ inch radial thickness, D being the diameter of the conductor in inches.

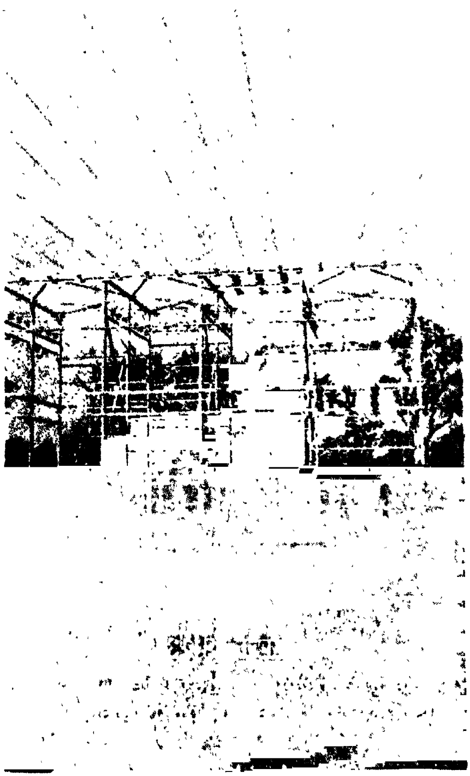


Fig. 8·22.

482. Types of Supports Employed in Transmission—Figs. 8·20-8·26

(*a*) *Wooden Poles, Fig. 8·29.*—These poles are useful for smaller spans, such as 250 to 300 feet, and low pressures. Under special conditions, where transportation charges of steel are high, special-designed H-type of poles are used for the lines having

working voltages up to 130,000 and average span 500 feet. The poles are strong in the transverse direction, but very elastic in the longitudinal one. For this reason anchor supports are provided by means of guys. The life of the poles is about 20 years, if properly impregnated with preserving substances such as creosote oil.

(*b*) *Steel Poles, Figs. 8·22-8·25.*—For longer spans tubular steel poles or narrow-base, lattice-steel masts are used. The life of this kind of support is longer than the wooden supports, and may be taken as 30 years If they are properly scraped and painted at regular intervals, they may have even longer life.

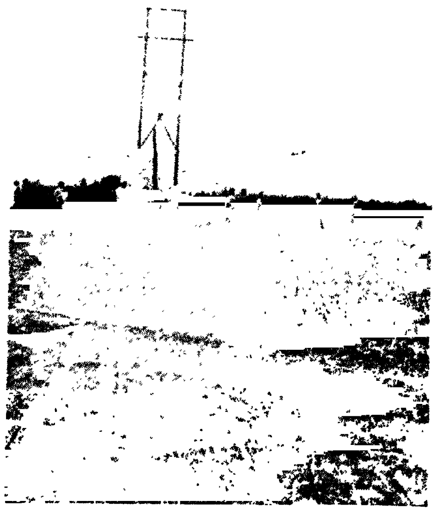


Fig. 8·23

(*c*) *Reinforced Concrete Poles.*—These are used for spans of about 250 feet. They are cheaper to maintain and the life is infinitely long.

(*d*) *Steel Towers, Figs. 8·20, 8·21 and 8·26.*—Where long spans have to be crossed, lattice towers are used. They are also adopted in long-distance transmission lines to minimise the number of supports. They have infinitely longer life and are more reliable than wooden supports. They withstand severe climatic condition and are immune from destruction by forest fires. The risk of interrupted service, due to broken or punctured insulators, is considerably reduced owing to

the longer spans rendered possible by the stronger and taller steel supports. Lightning troubles are also minimised as each tower is a lightning conductor, whereas on wood pole lines shattered poles and wrecked line sections are not infrequent. At a moderate additional cost double-circuit towers can be provided, thus giving a further insurance against discontinuity of supply. In case of break-down to one circuit, it is then possible to carry out repairs while maintaining the supply on the other circuit.

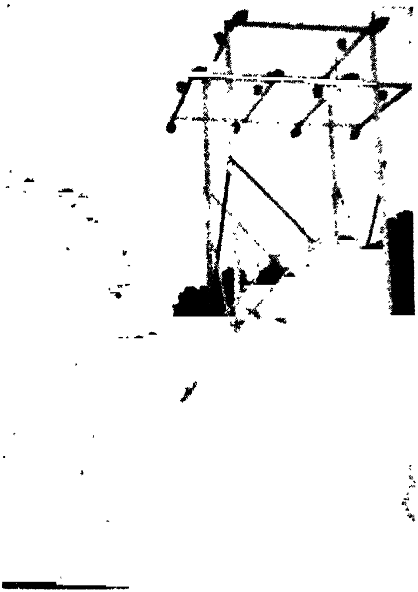


Fig. 8 24.

The steel structures are A-type or H-type. A-type poles are about 5 times and H-type poles about 3 times stronger than single poles, that could be economically provided. The wind-pressure on A and H-poles should be taken as 1·5 to 1·75 times, respectively, that on a single pole.

483. Diameter of Poles :—After considering the factors given for design, the average diameter of a round pole is found in the following manner. To determine the diameter, first find the wind-pressure on the wires. Note that the weight of the wires is not taken into account.

Let L=length of span in feet,

d=diameter of wire in feet,

H=average height of wires above ground in feet.

Fig. 8·25

n = number of wires,

H_p = height of pole out of ground in feet,

d_1 = average diameter of pole in feet,

P = maximum wind-pressure per square foot (here = 25 lbs.),

Wind-pressure on wires $= L \times d \times (2/3) \times n \times K$ ... (a)

Moment of wind-pressure one foot from ground line $= (a) \times H$ (b)

Wind pressure on pole $= H_p \times d_1 \times 2/3 \times K$ (c).

Moment of wind-pressure one foot from ground level $= (c) \times H_p/2$ ... (d)

Total amount $= (b) + (d)$ ... (e)

Breaking stress of required pole $= (e) \times 10$ (B. O. T. factor of safety). In India a factor of safety of 4 is prescribed.

Example 23.—Determine the breaking stress of the pole which is to carry 3 wires No. 19/0·125. Length of the span is 150 feet, length of the poles 30 feet out of ground, using metal poles having an average diameter of 6″.

Solution :—

The wind-pressure on the wires

$$= 3 \times 150 \times 25 \times (0·46/12) \times 2/3$$
$$= 288 \text{ lbs.}$$

If the average height of wires is 28 feet, the moment of wind pressure one foot from the ground line

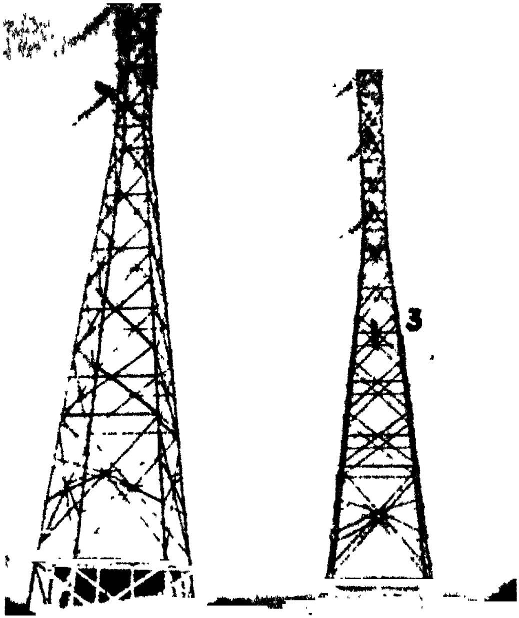
$$= 288 \times 28 = 8{,}064 \text{ lbs. ft.}$$

Wind-pressure on pole $= 30 \times (2/3) \times 25 \times 6/12 =$ 250 lbs.

Moment of pressure on pole $= 250 \times 30/2 = 3{,}750$ lbs. ft.

Total moment $= 8{,}064 + 3{,}750 = 11{,}814$ lbs. ft.

Then the pole (unless stayed all round) ought to have a breaking stress not less than 4 times; this is thus 47,256 lbs. ft or 1,700 lbs. applied 28 feet from ground level.



Steel Towers Used at Corners.

Fig. 8·26.

The diameters which are always measured 5 ft. from the butt, are controlled by the transverse wind-pressure on both poles and wires that the poles may have to withstand.

484. The stress acting on a pole at the top causes a tension in the fibre of the wood on one side of the pole and a compression on the opposite side.

For a round pole the maximum fibre stress is—

$$f = \frac{384PL}{3{\cdot}14d^3} \text{ lbs. per sq. in.,}$$

in which P is the pull at right angles in pounds at the distance L feet above the ground and d the diameter at the ground line in inches. The unit stress f should be taken not more than 10 to 12 per cent. of the ultimate breaking strength.

$$\text{or, } d = \sqrt[3]{\frac{384\ PL}{3{\cdot}14\ f}} \text{ inches.}$$

Example 24.—If a self-sustaining (unguyed) pole of Sal wood, ultimate breaking strength 11,000 lbs., is to support a line which exerts a horizontal pull of 800 lbs. at a height of 30 feet above the ground, what should be its diameter at the ground line to safely carry the load ?

Solution :—

f = 1/10 of 11,000=1,100 ; P=800, L=30 ft.

$$d = \sqrt[3]{\frac{384 \times 800 \times 30}{3{\cdot}14 \times 1{,}100}} = 13{\cdot}4''$$

A rough and ready rule is sometimes used that the wind-pressure on the pole itself is about equal to that on five No. 6 S. W. G weatherproof wires.

It is usual to select wooden poles with 7-in. tops for important distributing lines.

485. Stress on Poles on Uneven Ground (Glover's Vade-mecum) :—On hills, when poles are planted at different levels, the stresses on each must be calculated individually.

The point of maximum dip in the wires will not fall in the centre of the span, but will depend on the difference in level of the two supports. This point first be determined. Compare Art 472 (c).

If x denote distance of max. dip from higher pole,

$l-x$ denote distance of max. dip from lower pole,

h denote difference in level between poles,
D denote normal dip,
D_1 denote max. dip from higher pole, including difference in level of poles.

Then,

$$x = l \times \frac{\sqrt{D_1}}{\sqrt{D_1 - h} + \sqrt{D_1}}$$

The stress on the higher and lower poles, respectively, will then be calculated as if there were two spans $2x$ and $2(l-x)$ in length.

Example 25.—Assume that in the sum considered above there is a hill having a gradient of 1 in 15.

Then, $h = 20$.
D_1 (at 22° F.) $= 2{\cdot}8$ feet $+ 10$ feet
$l = 150$ feet. Determine x.

Solution :—

$$x = 150 \times \frac{\sqrt{12{\cdot}8}}{\sqrt{12{\cdot}8 - 10} + \sqrt{12{\cdot}8}} = 115 \text{ feet}$$

The stress on poles must be calculated as if there were two spans 230 ft. and 70 ft. in length, respectively

In the case of long spans across ravines, etc., the calculations may depend on the maximum stress to which wire can be subjected, and the question of dip be immaterial. Then the following formula may be used :—

$$x = l/2 + h \times s/w \times l$$

The principal danger when crossing rough ground is that of planting poles in hollows in such positions that there is an upward pull on the insulators. If the equation $h/4D$ has a value greater than unity at lowest temperature, then this condition exists and the span should be redesigned.

486. Concrete Poles :—These are used with advantage in the transmission of electric energy at high pressures. In Switzerland the ordinary wooden poles with concrete mortar about one inch thick have been used and the strength of the line has been found greatly

increased. But poles made of iron embedded in cement will last almost indefinitely without suffering any deterioration and as an additional advantage which they share with iron poles is that they are virtually so many lightning rods The use of concrete poles is not desirable for general distribution purposes where it is necessary for primary lines to be handled alive, because of the risk to line-men. These are used for street lighting.

The cross-section of the pole is a square with chamfered corners, the tapering being 1 in 120. The reinforcing bars should be covered with concrete to a depth of not less than one inch. The hollow poles have the advantage of increased strength for the same weight of material A factor of safety of four is usually taken.

The period of seasoning lasts from thirty to sixty days. The comparative rigidity and weight are the distinct disadvantages.

Calculation of a Ferro-Concrete Post for a Transmission Line

Example 26.—Design a ferro-concrete post for carrying 6 copper wires No. 0000 S. W. G., length of span 132′, and other data as stated below :—

Solution :—

The wire is No. 4/0 S. W. G., diameter 0·4.″

Spacing between wires 2′-6″=30.″

Provide for 3 sets of lines, *i.e.*, 6 wires in 3 sets. One set 12″ below the top.

∴ total length for 3 sets=5′.

Depth of pole underground, 5′.

Allow for sag, etc., and clearance, 2′.

Minimum height above ground, 20′.

∴ length of post=5+5+2+20+1=33′

Length of span=132′.

(*a*) Wind-pressure on the 6 wires

$$= 0{\cdot}6 \times 0{\cdot}4 \times 25 \times 132 \times 6 \text{ lbs.}$$

B. M. at a height of 24·5′

$$= 0{\cdot}6 \times 0{\cdot}4 \times 25 \times 132 \times 6 \times 24{\cdot}5$$
$$= 116{,}424 \text{ inch lbs.}$$

Assume the section, 12″ at bottom, 8″ at top.

(*b*) Wind-pressure on the pole

$$= \{8 + 12/2\} \times 28 \times 25$$

This acts at the midpoint above the ground, *i.e.*, 28/2.

$\therefore$ $B.\ M. = 10 \times 28 \times 25 \times 14 = 98{,}000$ inch lbs.

Total $B.\ M. = 116{,}424 + 98{,}000$.

$= 214{,}424$ inch lbs, approximately.

Taking the reinforcement 1·25″ below surface,

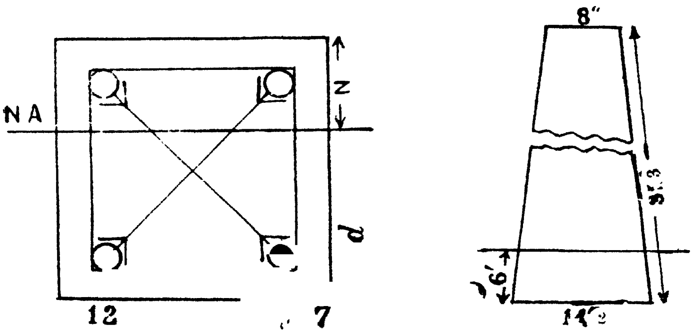
$$\text{value of } \frac{B}{bd^2} = \frac{214{,}424}{(12)\,(10 \cdot 75)^2} = 154$$

From tables—percentage reinforcement in steel = 1·1.
Sectional area of steel,

$$A_t = \frac{1 \cdot 1 \times 12 \times 10 \cdot 75}{100} = 1 \cdot 42 \text{ sq. in.}$$

Let E_a the modulus of Elast of Steel.

E_b the modulus of Elast of Concrete.



Section Showing the Reinforcement.

Fig. 8·27.

p indicates the percentage of bottom reinforcement.
and p' indicates the percentage of top reinforcement,
$n = E_a/E_b$, ρ_a the tensile stress in steel,
and ρ_b the compressive stress in concrete.

Then $Y/h = -n'p + 2/3\ p') + \sqrt{n^2\ (p + 2/3\ p')^2 + 2\ np}$ (*i*)

$B.\ M. = bh^2\rho_b\ (Y/2h + 2/3\ p'n)\ (1 - Y/3h)$ ... (*ii*)

$\rho_a/\rho_b = Y/2\ ph + 2\ p'n/3\ p$ ... (*iii*)

Taking this example into consideration, we are given :—

$b=12''$, $h_m=12''$, $h=12-1{\cdot}25=10{\cdot}75''$, $n=15''$

A area of bottom reinforcement$=1{\cdot}42$ sq. in.

A' area of top reinforcement$=1{\cdot}42$ sq. in.

$B.\ M=214{,}424$ inch lbs.

$\therefore\ p=(1{\cdot}42/12)\times 10{\cdot}75=0{\cdot}011=p'$

From equation (i) we get

$$Y=h\{-n\ (p+2/3\ p')+\sqrt{n^2\ (p+2/3p')^2+2np}\}$$

$$=10{\cdot}75\{-15\ (0{\cdot}011+(2/3)\times 0{\cdot}011)+\sqrt{15^2\ (0{\cdot}011+2/3\times 0{\cdot}011)^2+2\times 15\times 0{\cdot}011}\}$$

$$=10{\cdot}75\times 0{\cdot}362=3{\cdot}9''$$

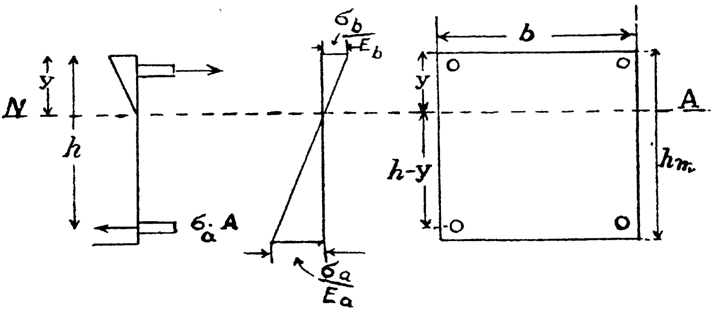


Fig. 8·28.

From equation (ii) we get

$B.\ M.=bh^2\ \rho_b\ (Y/2h+\frac{2}{3}p'\ n)\ (1-Y/3h)$

$214{,}424=12\times 10{\cdot}75^2\times\rho_b\ (0{\cdot}362/2+\frac{2}{3}\times 0{\cdot}011\times 15)$
$(1-0{\cdot}362/3)$

$\therefore\ \rho_b=214{,}424/12\times 10{\cdot}75^2\times 0{\cdot}291\times 0{\cdot}879=604$ lbs. sq. ins. Hence, the compressive stress in concrete will be 604 lbs./sq. in., which is within the safe working stress.

From equation (iii) we get

$$\frac{\rho_a}{\rho}=\frac{Y}{2\ ph}+\frac{2\ p'n}{3\ p}=\frac{0{\cdot}362}{2\times 0{\cdot}011}+\frac{2\times 0{\cdot}011\times 15}{3\times 0{\cdot}011}$$

$$=16{\cdot}45+10=26{\cdot}45$$

Hence $\rho_a=26{\cdot}45\times\rho_b=26{\cdot}45\times 604=15{,}975$ lbs. sq. in. The tensile stress in the reinforcement bars would be 15,975 lbs. sq. ins., which is also within the safe working limits.

The reinforcement works out to 4 rods of 1″ dia.
Cost of pole, 33 feet high, when proportion is—

Cement	100 c. ft.	@ Rs.	212/8/-
Sand	200 ,,	@ Rs.	8/-
Gravel	400 ,,	@ Rs.	32/-

$$\text{Volume} = \frac{10'' \times 10'' \times 33'}{144} = 23 \text{ c. ft.}$$

$$\text{Weight of steel} = \frac{1\ 42 \times 2 \times 33 \times 480}{144} = 2{\cdot}79 \text{ cwt.}$$

Binding wires, etc., say, 0·41 cwt.

Total steel = 3 2 cwt. @ Rs. 6/- per cwt.

∴ Concrete	...	Rs. 8/5/-
Mould	...	Rs. 6/-
Steel	...	Rs. 19/3/-
Labour	...	Rs. 18/-
Total	...	Rs. 51/8/-
Contingency	...	Rs. 2/-
Total	...	Rs. 53/8/-

The cost of transport and erection is great as the posts are very heavy. So they may be made near the place where they are required.

487. Ground Clearance:—The height of the support is determined from the allowed ground clearance between the lowest conductors and the ground. The usual value is 20 ft. The British regulations for the clearance for the overhead lines are as follows:—

Voltages up to 66,000 volts	...	20 feet.
66,000 volts to 110,000 volts	...	21 feet.
110,000 volts to 165,000 volts	...	22 feet.
Voltages over 165,000 volts	...	23 feet.

For road-crossing a clearance of 25 feet is generally given. Navigable rivers and canals require a large clearance, and towers as high as 300 feet are used in such cases. The cost of such towers is excessive, and to avoid this the line is crossed at such place of the river where big cliffs, if possible, are obtained. No conductor of an aerial line (not being a trolley-wire or a traction feeder on the same support as a trolley-wire), erected in,

over, along or across any street, shall be at a less height from the ground than 20 feet, nor shall it be accessible, either from the ground or from any permanent structure, except by the aid of a ladder or other special appliance.

Where such an aerial line is on a consumer's or an owner's premises, the height from the ground shall be not less than 15 ft.

The minimum length of the pole should be as follows :—

In ground	6′-0″
Distance from pole-top to the lowest wire	(say) 2′-6″
Allow for sag	,, 2′-10″
Minimum height from ground ...	20′-0″
Over-all length of pole ...	31′-4″

A continuous earth wire shall be carried from pole to pole and shall be well-connected to substantial earth plates at intervals of not more than five spans, or their work on each pole shall be connected to a substantial earth plate.

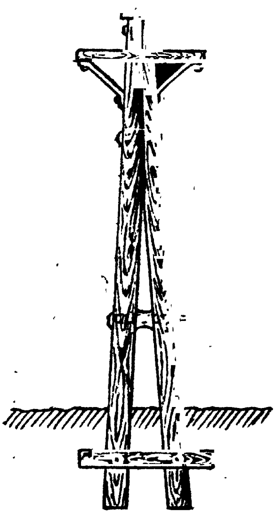


Fig. 8'29.

488. Construction of Wooden Poles :—Single poles are used ordinarily, but where greater strength is required, "A" poles are used, in which two members having requisite strength are set at an angle of about 10°. This would sustain, in a direction across its two members, a load 4 or 5 times as great as an unstayed single pole of the same diameter as either of the members. End and corner poles should be braced.

489. Spacing of Poles :—Spacing of poles will be determined by weight of pole used, number of wires carried, liability to sleet and ice, storms, or to high winds.

The whole of the route should be surveyed with a theodolite and each pole's position be pegged out before any work is commenced. Where the line crosses uneven ground, poles should, as far as possible, be placed at the highest points. In hilly or broken country the support must be erected at advantageous points, regardless of the varied lengths of span that may result. For level or undulating country a standard span ranging from 100 to 800 ft. may be used. It is well to keep the consecutive spans in a transmission line, as nearly as possible, of the same length, to avoid unbalancing of the tensions in adjoining spans with every change of temperature.. With increased length of span the number of structures and insulators is decreased (hence maintenance charges), but the height of the tower is increased. Other things being equal, the span should be so selected that the total line-cost is a minimum. For river and ravine crossings exceptionally long spans are required. Under such conditions, very big spans from 4,000 to 6,000 feet have been satisfactorily employed. The conductor in this case is steel-cored aluminium, copper-clad steel, or simply galvanised steel.

The mechanical consideration of the line, where the economic section is very small, such as 8 S. W. G., restricts the use of longer span than 150 feet as the sag then becomes excessive. In the cases where the economic section becomes small, it is often possible to reduce the total line cost by using a larger and stronger conductor and increasing the spacing of the line.

Spacing in the case of poles should not exceed 40 to 45 yards—for heavy power lines 26 yards and for ordinary electric and power lines 33 to 45 yards. "Thirty poles to the mile is a minimum permissible number and is poor practice. Forty poles per mile is better and is considerd good practice. Fifty poles, or with spacings of about 100 feet, is much to be preferred, specially if the one is installed where the number of conductor carried is liable to increase. And where heavy work is to be installed at once, the number of poles per mile may still further be increased. Careful spacing

near corners will permit double pole corners, which are much to be preferred" (O. J. Ferguson).

490. Planting Poles :—Poles should be set in earth to a depth of $\frac{1}{8}$ to $\frac{1}{5}$ of their lengths for tall and short poles, respectively, and at least 5 feet in the ground with an addition of 6 inches for every 5-feet increase in length over 35 ft. Special care in setting is necessary when the ground is soft ; end or corner pole should be braced and at least 10th pole along the line should be guyed with 1/4 or 3/8 inch stranded galvanised iron wire.

Length of poles	...	20′	30′	40′	50′	60′	70′	80′
Depth	...	4′	5′	6′	7′	$7\frac{1}{2}$′	8′	$8\frac{1}{2}$′

In rock these depths can be reduced by one-third.

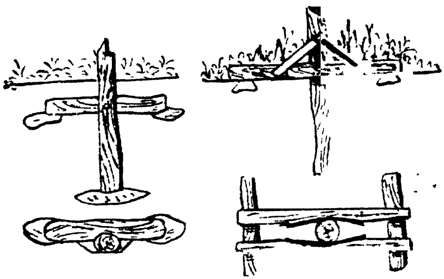
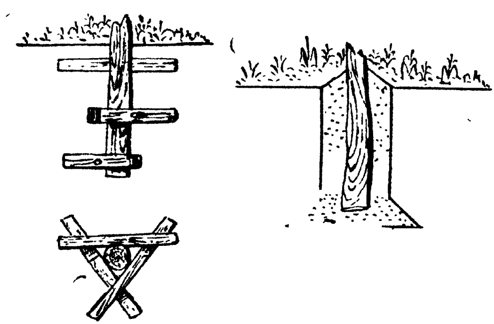


Fig. 8·30.



Pole Setting in Unstable Earth

Fig. 8 31.

Char and tar the butts of poles before setting. This is done by placing the pole over a slow fire, gradually revolving it until the butt, at least about one foot above the ground level, is thoroughly charred ; while hot it is given two or three coats of tar with a stiff brush and is then set. The pole should be planted in one corner of the hole and the pole-hole dug in the direction of the line and as narrow as possible. The earth should be piled a foot higher than the ground level.

A concrete foundation consisting of cement 1 part, sand 3 parts, stone or brick 6 parts, mixed wet, may be used for wooden poles, where exceptional stability is required. This concrete filling should extend at least a foot from the poles on all sides, and should be carried above the ground line and levelled to shed water.

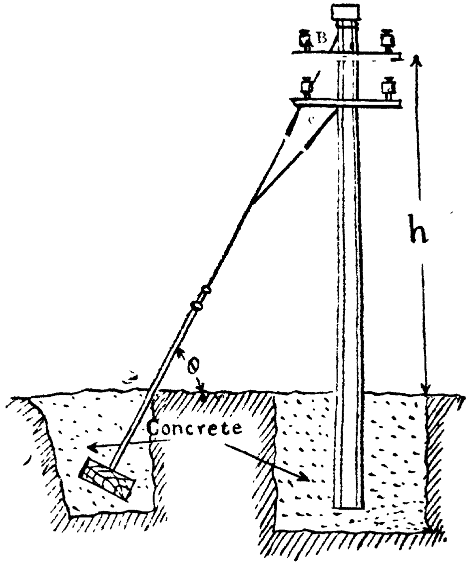


Fig. 8·32.

491. Cross-Arm.—The length is determined by the number of conductors to be carried and also the transmission voltage.

If $2l$=length of the cross-arm in centimetres,
b=breadth of the cross-arm,
d=depth of the cross-arm,
w=total weight in kilogrammes resting on one insulator,
s=the maximum permissible fibre stress of the cross-arm in kilogrammes per square centimetre, then

$$s=6\ wl/bd^2.$$

Allow a factor of safety between 4 and 10. The cross-arms should be spaced at least 24 inches between centres, the top arm being placed 12 inches below the top of the pole. For circuits up to 5,000 volts $3\frac{1}{2}$ by $4\frac{1}{2}$ inch cross-arms with spacing between pins of 12 or $14\frac{1}{2}$ ins. are used and the pole pins spaced 22 inches;
up to 6,600 volts—2 ft. 4 ins;
from 10,000 to 20,000 volts—3 ft. 4 ins;

from 20,000 to 30,000 volts—4 ft. ;
from 30,000 to 50,000 volts—5 ft. ;
from 50,000 to 60,000 volts—6 ft.

For higher voltages special cross-arms and spacings are necessary. The usual method of treatment is to paint them with white lead and oil.

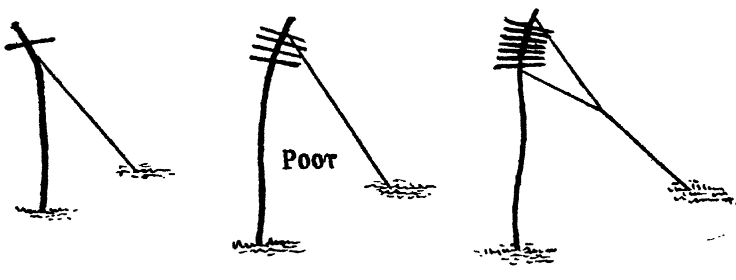
492. Stays and Struts :—The stresses due to the weight of the wires should be balanced by stays or struts at corners and terminals. *i.e.*, (1) to strengthen the line at angles or terminal points, (2) to bring up the construction on straight lengths to the required strength where the poles are not strong enough, (3) serve to prevent the wires blowing together in winds.

The G. P. O. in their instructions regarding stays, say :—In order to secure the full efficiency of a stay, the following conditions should be observed :

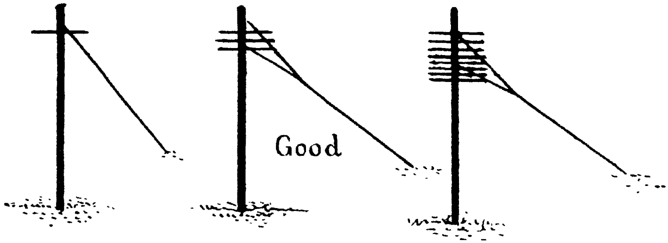
Its upper end should be attached, if possible, above the line wires, or as nearly as possible at the resultant point, where all the forces acting upon a pole can be balanced by an equal and opposing force. This point may be taken approximately at about the middle point between the upper and lower arms. It should never be fixed below the line wires.

Its lower end should be attached to a stay-rod fitted with an adjustable stay-tightener.

It should be fixed firmly and rigidly in the ground.



Poor Methods of Attaching Guys to Pole Heads.
Fig. 8·33.



Good Methods of Attaching Guys to Pole Heads.

Fig. 8·34.

It should, so far as circumstances will permit, be so fixed as to make a reasonably large angle with the pole.

It is better to fix a stay in each alignment rather than only one in a resultant direction.

A stay should be carried well away from the pole.

Cross-arms should be spaced at least 24 inches between centres, the top arm being placed at least 12 inches below the top of the pole. They are placed on the alternate sides of poles. On corners and curves double arms are used. The most efficient direction in which a stay could be fixed would be at right angles to the pole, and as the angle diminishes to an acute angle and eventually coincides with the pole, so the efficiency of the stay decreases. Generally speaking, for transverse stay the base should not exceed half the height of the resultant point above the ground. For terminal stays, it should equal that height.

At least every tenth pole in the line should be guyed with $\frac{1}{4}$ or $\frac{3}{8}$ inch stranded galvanised iron wire. Where there is but one guy per pole, it is made up around the pole just under the top cross-arm at *B*. Where there are two guys to the pole, one is made up just under the top cross-arm at *B* and one just under the bottom cross-arm at *C* (Fig. 8·34).

Where more than two guys are used, the additional ones should be spaced as equally as possible between the top and the bottom guys that are made up under the top and bottom cross-arms, respectively.

Where there are two or more guys to the pole, each should be independent of the others and the different guys should not cross one another.

Guy stubs are set in the ground at an inclination such that the guy makes an angle of 90° with the stub or with the axis of the stub in the direction of the guy, the stub in the latter case being in the place by a timber or plate fastened at right angles to the bottom of the stub. Such a timber is known as a "dead man." The stay wire must run straight to the anchor with no angle at ground level or supplement of the angles contained by the line wires. It is best to undercut the hole for the anchor and to cut a slot in the ground for the stay wire Where a wash-out is likely to occur in heavy rain, 4 stays are sometimes advisable, two across and two along the line, to limit the trouble in case of breakage of the line.

The resultant stress in the line wires is :—

At terminals ... ... $s \times n$

At angles ... ... $2\,(s \times n) \times \sin\,\theta/2$

When :—

s denotes stress due to weight of 1 wire,

n ,, number of wires.

θ ,, angle of deviation.

The stress in a stay wire, fixed to counteract the resultant stress in the line wire, is :—

$$\frac{\text{Resultant stress in line wires} \times \text{length of stay.}}{\text{Distance between base of stay and base of pole.}}$$

If the stay has to be fixed below the line wires, the figure should be multiplied by H/h,

where H=height above ground of resultant line pull, and

h=height above ground of point at which the stay is fastened to the pole.

Galvanised steel wire is customarily manufactured in strengths of 25 tons, and 60 tons per sq. in. A safety factor of 4 should be allowed in the stay wire.

The stay should be anchored to a creosoted wood baulk buried 5 ft. in the ground undercutting so that

the major portion of the baulk bears against undisturbed ground.

Sometimes it is difficult to provide stay wires; or impurities in the atmosphere may render the use of struts preferable to stay wires. In such cases, it is necessary to know approximately what load a wooden pole will support in compression. Assuming a factor of safety of 10, the working load W (in lbs.) that can be supported by a pole of average quality and circular cross-section is approximately as,

$$W = \frac{800\,d^4}{H^2},$$

where d is the average diameter of the pole in inches, and H is the length in feet.

The chief point to remember when planting strutted poles, is that the stress is always such as to tend to lift the pole out of the ground. A substantial kicking block should, therefore, always be used resting so far as practicable against undisturbed soil.

The G. P. O. recommend that :—

"Struts should make a reasonably wide angle with the poles they support, for their effectiveness depends upon the same principle as that which determines the efficiency of stays. They should act both as stays and struts, so that in whichever direction storms may act upon a line, the struts shall be found sufficiently strong to resist the impressed stresses.

"Struts should not weaken a pole, and it is, therefore, objectionable to make incisions or mortises in the pole for the purpose of fixing the strut. The end of the strut should be brought to a feather edge, and should be carefully and neatly scarfed to fit the pole, and the points which are brought into contact should be coated with a mixture of coal-tar and creosote so as to make a sound, watertight joint. One 5/8-in. bolt should be used to fasten the head of the strut to the pole, the bolt being placed at the bottom of the scarfed portion. A tie-bolt of suitable length should be fixed between the pole and the strut, about midway between the apex of the triangle and the ground."

The guys or stays shall be securely anchored and earthed.

Stacks from 60 ft. to 125 ft. high should have two sets of 4 guys, each attached at $\frac{2}{9}H$ and $\frac{4}{9}H$, respectively. Guy wires should make an angle of 45° with the stack and should have a minimum thickness of $\frac{1}{2}''$.

Example 27.—Terminal Stay.—A line of 3 No. 4/0 wires (breaking strain $1,750 \times 4 = 7,000$ lbs.) is terminated on a pole and the stay is to carry the load. Determine the tension to be taken by the stay.

Solution.—

If the wires have been erected to have a factor of safety of 4, the tension which 3 such wires will exert on a terminal post will be $3 \times 7,000 \times 1/4 = 5.250$ lbs.

The tension to be taken by the stay would then be $5,250/\sin \theta$, where θ is the angle which the stay makes with the post.

If fixed at right angles in continuation with the line wire, the tension is 5,250 lbs. ; at 45° it is 7,400 lbs., at 30° it is 10,400. If the factor of safety is 4, it should have a breaking load of $(7,400 \times 4) = 29,600$ lbs. for 45° and $(10,400 \times 4) = 41,600$ lbs. at 30°. Iron stay wire may be taken as having a breaking load in lbs. of about $3\frac{1}{3}$ times its weight per mile, so that the stranded wire used should be equal to 8,900 lbs. and 12,500 lbs. per mile in the two cases. For steel 1/3 or less of these weights per mile would be sufficient according to the materials used.

Example 28.—Angle Stay.—Determine the angle stay when $\theta = 60°$.

Solution.—

The resultant load $R = z\ (s \times n)\ \sin \theta/2$

where s=stress or the tension of one wire due to weight of one wire,

n=number of wires,

θ=angle of deviation or supplement of the angle contained by the line wires.

Thus suppose the 3 No. 4/0 wires all make a horizontal angle of 120°, where the line changes its direction at a certain angle pole so that $\theta=60°$. The tension of the 3 wires is, as before, 5,250 lbs.; so $R=2\times 5{,}250\times \sin 60/2=5{,}250$ lbs.; so a single resultant stay will be of the same size as the terminal stay already worked out above.

493. Transposition :—Transpositions are made to eliminate, electrostatic and electromagnetic unbalancing of the various phases, to eliminate mutual induction between parallel lines and to prevent disturbances in neighbouring telephone and telegraph circuits.

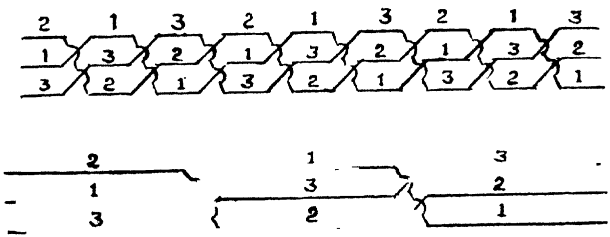


Fig. 8·35.

A complete transposition of a three-phase line in a given distance is obtained by making each wire occupy the same position relatively to the ground and to the supporting structures over one-third of the distance.

These are commonly made by rotating the delta, by gradually changing the relative positions of the wires by dead ends and jumpers. Transposition spans are about one-half the length of standard spans in order that proper clearance between conductors may be maintained.

On a long line complete transposition every 10 miles should be sufficient. The present tendency is towards avoidance of transpositions of the power conductors on transmission lines of lower voltage carried on wooden poles about 150 feet apart The transposition of telephone wires is frequently made at every fourth or fifth pole, but it is generally more satisfactory to transpose at every pole. The distance between power line transpositions is a matter of judgment, and may vary from 10 to 40 miles.

494. Interconnected System.

Advantages of Interconnected System :—

1. The exchange of power from one system or plant to another is highly desirable in emergency situations such as (*a*) at times when steam power can be produced on one system at a lower rate than on another, and (*b*) in case of hydro-electric plants—at times of low flow.

2. Prompt loading of large plants.

3. Large steam units and a location selected with regard to the fuel.

4. Continuity of service is well assured far beyond what can be obtained from any single or local source of supply.

5. It reduces total reserve capacity over the aggregate amount required in separately-operated system and utilises the reserve capacity to better advantage.

6. In hydro-electric plants, it enables the undertaking to take advantage of the diversity of the natural stream flow between catchment areas and to reduce the amount of reserve steam power to guarantee continuous service.

7. The installation of the transmission line and interconnection would do away with the waste of power due to unequal distribution of rain in areas having different stations.

8. Less danger of complete or extended shut-down by relaying of power.

9. Fluctuation of large individual loads are relatively less.

10. The effective capacity of two or more generating stations is often increased 25 % by interconnection, owing to the improvement of the diversity factor.

11. The interconnected system is advantageously employed on the Thury constant-current transmission system.

12. Much benefit is derived when the time load curves of two stations are of different character, *i.e.*, the

peak load on the stations occur at different times of the day. The greater the difference in the peak load and time, the more the advantage.

13. When two hydro-electric plants operate by the same source of water power at two different levels, the electrical load can be distributed so as to utilise the additional water flow at the upper level without a storage at the downstream station (Mandi Hydro-Electric Scheme; Ganges Canal Hydro-Electric Scheme).

14. Many small water power schemes, which would be commercially worthless, if developed independently, can profitably be tied together to an existing network.

15. A superior technical and operating staff is available.

Disadvantages :—1. The destructive energy in cases of failure may be increased.

2. The different parts of the system may be highly strained.

3. Troubles causing a complete shut-down affect more consumers.

4. Disturbances are communicated between systems.

5. Surge occurs more often and is likely to be more violent; hence better insulation may be required.

6. The rupturing capacity required in some of the switches may be increased.

7. Operating difficulties are usually increased.

8. Frequency difference is a more serious factor owing to the fact that it involves the use of frequency changers which are rotating machines; they suffer from 'swinging' or 'hunting' difficulties because a certain mechanical displacement of the motor corresponds to a higher electrical displacement on the high-frequency than on the low-frequency side of the machine.

CHAPTER IX

DISTRIBUTION

***495. The Requisites of Power Plants and Distribution Systems :—**

I. SAFETY TO OPERATORS AND EQUIPMENT, which requires :—

(*a*) Voltage not unnecessarily high.
(*b*) Adequate insulation of lines and equipment.
(*c*) Protection against lightning and other excessive voltage.
(*d*) Automatic protection against grounds, short-circuits, and overloads.

II. CONTINUITY OF SERVICE, which requires :—

(*a*) All that is required for safety.
(*b*) Duplication of all essential equipment.
(*c*) Circuit-breakers that do not operate instantly, and some interlocking arrangement that keeps one breaker in, when another goes out.

III. SMALL FIRST COST, FIXED CHARGES AND OPERATING COST, which require :—

(*a*) All that is required for safety.
(*b*) Voltage neither too high nor too low.
(*c*) Labour-saving apparatus without unnecessary complications.
(*d*) Installation of no unnecessary equipment.
(*e*) Generating and other units neither too large nor too small.
(*f*) Units of high efficiency, operating at about their maximum efficiency.
(*g*) Equipment having little depreciation.

Brown's Electrical Equipment.

(*h*) Equipment requiring little outlay for upkeep and repairs.

(*i*) Conditions of low interest, insurance and taxes.

IV. SMALL PER CENT. VOLTAGE VARIATION, which requires :

(*a*) & (*b*) High-line voltage or large-line wires for small per cent. drop.

(*c*) & (*d*) Suitable compounding or voltage regulation of D. C. generators, voltage regulation of A. C. generators, or regulation of feeder voltage, or any combination of these methods of regulation.

(*e*) Power factor of the A. C. load as high as possible.

V. ADAPTABILITY TO ALL REQUIRED LOADS, which requires :—

(*a*) Sufficient total capacity of generating units.

(*b*) Capacities of some or all the units not much in excess of the minimum load.

(*c*) Allowance for expansion.

(*d*) Ammeters and wattmeters whose full-scale indications are sufficient for all ordinary overloads, and whose indications at customary loads are reliable with fair accuracy.

VI. Good appearance, which encourages keeping the plant in good condition, and requires :—

(*a*) Consideration of appearance in selecting equipment.

(*b*) Orderly lay-out of switchboard and machines.

(*c*) Good building.

(*d*) Well-arranged natural and artificial lighting.

496. Classification of Systems :—Distributing circuits may be classified—

(1) as to the nature of the current—direct or alternating ;

(2) as to the method of connection—series or multiple ;

(3) as to phases, number of conductors, voltage and frequency.

Direct current is best adapted:—

(*a*) where distances are small,
(*b*) where there is variable speed machinery, and
(*c*) where there is an area of congested load for which storage-battery reserve is necessary to ensure continuous service,
(*d*) For domestic supply.

Alternating current is best adapted to use where the distances are greater and the density of the load not sufficient to justify low-tension distribution without transformation from a higher voltage.

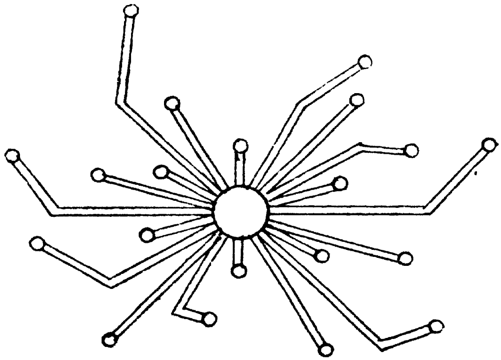
Comparison of Systems of Distribution for General Power and Lighting Purposes.

Type of System.	Connection to Earth.	Relative currents in the main conductors for the same kW. transmitted.	Relative total weight of conductors per mile for the same kW. capacity.	Relative loss in transmitting same kW. over same distances	Relative distance of transmission for the same percentage volt-drop.	Maximum volts between any conductor and earth.	Maximum volts between any pair of conductors.
D. C. or A. C. 2-wire.	One pole earthed, if desired natural.	100	100	100	1	V.	V.
D. C. 3-wire.	Earthed ...	50	62·5	50	2	V.	2V.
A. C. 3-phase 3-wire.	Do. ...	57·8	86·6	86·6	1·15	·577V.	V.
A. C. 3-phase 4-wire.	Do. ...	33·3	58·3	50	2	V.	1·732V.

Lighting voltage = V. throughout. All mains run at the same current density.

497. Systems of Distribution :—There are four main systems of distribution : (*a*) simple radial, (*b*) series radial, (*c*) Tee-system, (*d*) interconnected system.

(*a*) **A simple radial system,** with duplicate feeders, direct from the power-house to each sub-station, is equipped with time-limit overload relays at the power station and reverse power relays at the sub-station end. This limits the risk of interruption to the sub-station fed by the faulty feeder, but owing to the defects of the protective arrangements, it cannot ensure complete continuity of supply to the sub-station affected



SIMPLE RADIAL

Fig. 9·01.

It has been used largely in America and also in this country for important supplies, such as railways.

(*b*) **Series radial system** is the modification of the above, but with direct feeders from the power station to the more important sub-station only, these feeding the remaining sub-stations in a similar manner. This involves graded overload gear, which is very unsatisfactory, and a faulty feeder may cause interruption to all sub-stations on the section very easily.

The use of series systems is limited almost entirely to street and other lighting which is all in use at the same time. These systems are inherently high-tension in character, and are, therefore, not suitable for general purposes. They are operated by direct current or

alternate current at a constant current of 5 amps. to 10 amps. in American practice. In Europe there are several direct-current series power-transmission systems in operation utilising a series of motor generators as the converting medium.

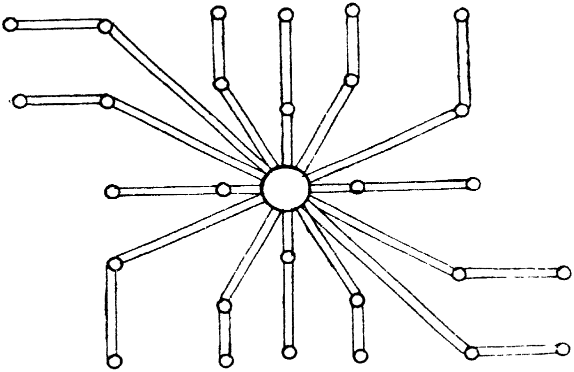
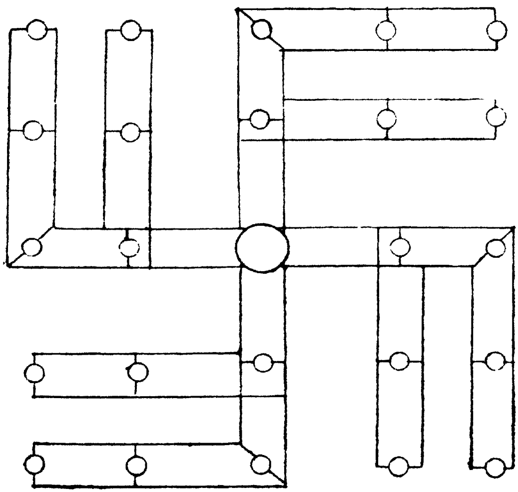


Fig. 9·02.

(c) **A Tee-system** is one in which a number of sub-stations are normally given, a non-duplicate supply from one feeder, and arrangements made in the sub-stations for the transfer of the loads to a duplicate feeder in case of emergency. This involves a short interruption to supply until the change-over is affected.



TEE · SYSTEM

Fig. 9·03.

In Tee-system of distribution, in case of house-wiring, the main cables are run through the building, being continuously reduced in size as the current diminishes at each point where the cable is reduced, and a fuse is placed.

Defect of this is that (1) fuses are scattered all over the building often in almost inaccessible places ; (2) in case of fuse blowing repairs are difficult even when the fuse which has blown is located ; (3) risk of fire, with so many fuses involved.

Continuous-Current One-Wire Distribution :— There is only one regular application in the operation of arc lamps. All the utilisation devices must be connected in series with each other and the current is the same throughout the circuit. Further, the line must be a closed circuit and, leaving the power-house in one direction, pass from lamp to lamp and work its way round until it arrives at the power-house again.

(*d*) **Multiple parallel system** or interconnected system is a system in which all the mains and sub-stations are connected together, and the duplicate supply given by the economical method of ring mains. This is the system now generally accepted

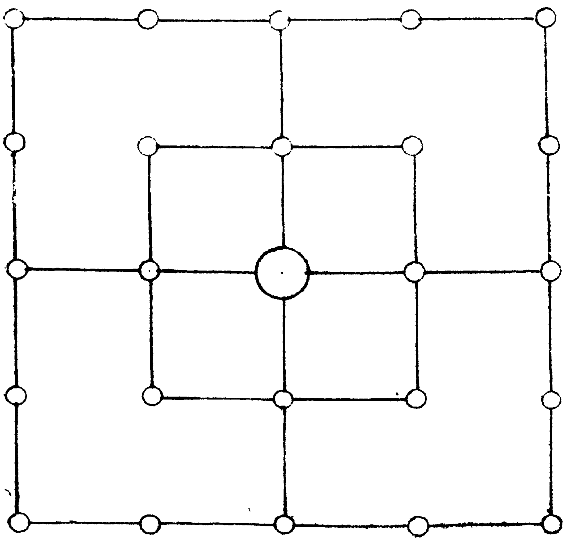


Fig. 9·04.

in every country. For such a system to operate satisfactorily, it is essential that each section be so protected that a faulty section is isolated instantaneously without serious shock to the rest of the system, and without disconnecting any healthy section, whatever may be the magnitude and direction of the current flowing through faulty sections.

The capacity of the ring must be sufficient to carry the combined load of all the units in case either of the links adjacent to the point of supply should fail. The feeders may be connected at the ends of the mains, known as parallel feeding, or they may be continued at opposite ends of the main, known as anti-parallel feeding.

It has not hitherto been found possible to protect completely a section of the main in this manner by apparatus in the sub-stations only, and some special construction of main and special pilot wires are always required. This increases the cost per mile of a given type of mains, but it is found invariably that the resultant savings, due to reduced mileage of mains, reduced number of switches, and the beneficial effects of diversity between demands at the various points of supply, are much more than compensate for the cost of protective gear The saving is particularly marked with higher voltages, more numerous sub-stations, larger areas of supply, and where the power stations are at some distance from the centre of the load.

498. Voltages Employed in Distribution :—When *direct current* is used, a nominal voltage of 110-230 for lighting and 550 for power distribution is adopted.

When *alternating* current is used, the primary mains are operated at a nominal voltage of 2,200. The low-tension distribution mains are operated from 110 to 400 volts for light and small power work. Single-phase, two-phase and three-phase circuits are in general use, with frequencies of 25 or 50 cycles. In general, single-phase distribution is used for lighting and small power service, and two-phase or three-phase distribution is used for large power loads.

British standard specification No. 77 gives the following standard electric pressures for new systems and installations.

D. C. Consumer's Pressure.		Declared Station Pressure.
220	...	242
440	...	464

Alternate current (three-phase system) and installation between neutral wire and each of the principal conductors:—

	Consumer's Pressure.		Station Pressure.
	240	...	264
Between phases	416	...	457

High pressure :—

Delivered Pressure.		Station Pressure.
3,000	...	3,300

Domestic supply for light and fan must never be more than 110-volt A. C.

The consumer's or declared pressure in the above classes shall be the pressure denoted as standard, the station pressure being derived by the addition thereto of the pressure lost in the line when carrying its full load ; unless otherwise specified, this loss shall be assumed to be such as to give the station pressure shown above. In higher station pressure than one of the values given above the purchaser shall state such pressure for machinery and material.

499. Voltage Drop :—(1) *The Voltage Drop Allowable in Lamp Circuits.*– For a 110-volt circuit, containing incandescent lamp load, the conductors should be of such size that the pressure at the terminals of the lamps can never vary more than 3 volts. Sometimes 4 and even 5 volts variation is allowed on 110-volt lamp circuits. This is not good practice. Expressed in percentages, an 1 per cent drop represents good practice ; a $4\frac{1}{2}$ per cent. drop is the upper limit. These are percentages of the receiver or normal lamp voltage. If the values above suggested are exceeded, the life of the lamps may be shortened or they may burn dimly when the circuits are loaded.

(2) *The Voltage Drop allowance in Motor Circuits.*—A drop of 5 per cent. is often permitted. If motors and lamps are on the same circuits, a 3 per cent. drop should not be exceeded. The conductor economy decides to a great extent the voltage drop in conductors. In important work, particularly where the cost of energy is high, the cost of the energy lost in a conductor, as well as the volts lost in it, should be considered.

Per cent. line drop or voltage loss may be given as either a percentage of the voltage required at the receiver or as a percentage of the voltage impressed by the generator or other energy source on the line.

Good practice shows the drop in potential to be within the following limits :—

Loss in sub-feeders—3 per cent.
Loss in main—1·5 per cent.
Loss in service wire—0·5 per cent.

The actual voltage variation should not exceed 3 %.

Example 1. The voltage impressed on the receivers—lamps and motor—is 220. The line loss is 10 volts; hence, the pressure impressed on the line=220+10=230 volts. The voltage loss as a percentage of the voltage at the receiver=10/220=4·5 per cent. The voltage loss at a percentage of the voltage impressed on the line is 10/230=4·35 per cent In practical work the percentage loss or drop is usually taken as a percentage of the voltage required at the receivers, because this is the most convenient and direct method The term "percentage drop" refers to percentage of the voltage required at the receivers, unless otherwise noted.

(3) *To ascertain the volts drop as a percentage of the volts impressed* on the line :—

$$V=\frac{EP}{100}\times\left(1-\frac{P}{100}\right),\text{ or } EP/(100-P)$$

where V=volts drop or loss in line, P=percentage drop of the voltage impressed on the line and E=voltage at the receiver.

Example 2. What will be the voltage drop in a circuit where 220 volts is to be impressed on the receivers—lamps, motors or other equipment—and the allowable drop is 3 per cent. of the voltage impressed on the circuit ?

Solution :—

$$V = EP/(100 - P) = 220 \times 3/(100 - 3)$$
$$= 660/97 = 6{\cdot}8 \text{ volts.}$$

500. To Determine Wire Sizes for Circuits.—Almost all wiring problems involve the finding of the size of wire that will carry a given current to a given distance with a given drop in volts.

(A) Determine the load in amperes that will come on the circuit. This ampere load value will be used in taking the wire size from a table or will be substituted for the letter I in a formula (Art. 504).

(B) Find the distance to the load centre of the circuit. This distance will be the actual length if the load is concentrated at the end or it will be the distance to the load centre if the load is distributed. When found, this distance is used as the length of the circuit and is substituted for the letter L in a formula (Art. 504).

(C) Decide what voltage drop or volts drop is allowable.

(D) Determine the wire size that will give the voltage drop decided on in C by using one of the formulæ that follow, using the values for distance and volts drop of B and C.

(E) Where economy of operation is a factor, check the size of conductor as determined ; be sure that the cost of the energy wasted in it in overcoming its resistance will not be excessive.

501. Factors Which Determine the Size of Wires in Practice.—Factors that should be considered when determining the sizes of wires for the distribution of electricity—A wire should be of such size that :—(1) it must have sufficient strength to withstand the mechanical stresses to which it may be subjected. This

condition applied specially to wires strung on poles; (2) in constant-voltage system the wire must be large enough to carry the electricity to the point where it will be used without an excessive drop or loss of voltage; (3) the current will not heat it to a temperature that would spoil the insulation or cause a fire; and (4) the cost of energy lost—I^2R—will not be excessive so as to give an economic balance between the cost of the copper and the cost of the power lost in the wire; (5) in extreme cases the size of a wire may be determined by a consideration of the electric strength of the air or other insulating substance surrounding the wire; in as much as the strength of an insulating medium to withstand the electric stress between wires, due to a given voltage between them, depends in part upon the size and shape of the wires.

502. For Bare Overhead Wire:—Prof. G. Forbes has given the current which can be carried without overheating.

$$I^2 = D \frac{\pi^2 H}{4 \rho \times 0.24} = \frac{D^3 t}{320 \rho}$$

Where I = current in amperes.
D = diameter of wire in centimeters.
T = excess of temperature of wire over air in degrees centigrade.
H = coefficient of radiation.
K = coefficient of radiation for heat of the insulation.
(For gutta-percha $K = 0.000486$ and for India rubber $K = 0.000405$).
Convection = 0.0003
ρ = specific resistance of material at limiting temperature in volumes per circuit.
0.24 = calorie in Joule.

For insulated overhead wires:—

$$I = \sqrt{\left\{ \frac{\pi^2 K D^2}{0.48} \times t \times \frac{3 D_2}{10 + 3 D_2 \log_e \frac{D_2}{D_1}} \right\}}$$

Where D_1 = diameter of core in centimetres.
D_2 = diameter of outside insulation in centimetres.

Where any one of these conditions demands a larger wire than would be required by any of the other conditions, the large wire should be used. Very often an engineer is guided by one only of the above conditions in laying out the preliminary plans for a distributing system. When this is the case, the preliminary plans should be examined carefully to see that all of the conditions are satisfied before the plans are finally adopted.

503. The minimum size of the conductors within a building will be determined as follows :— It is customary to assume each lamp to take 60 watts, but it is safe to take 30 watts for estimating purpose at the present day.

(1) *Lighting Circuits* :—By the permissible drop in volts, which, under ordinary conditions, must not exceed 2 per cent. *plus* a constant allowance : thus the area of all conductors inside the buildings should be so proportioned to their length that the drop in pressure between the main fuses and the farthest or any lamp shall not exceed 2 per cent. with all the lamps alight The allowable drop of pressure in the sub-mains is about 1 per cent.

Branch circuits are limited to about 6 to 1 lamp., or 2 to 3 fans, or one heating and cooking appliance each. Note that a drop of about 6 to 10 per cent. is generally allowed with non-inductive lighting load and of 20 to 25 per cent on a load with a power factor of 0·8, where drop means the ratio of the difference between the full-load and no-load terminal voltage, to the no-load voltage of an alternator running at constant speed, with the normal full-load exciting current.

(2) *Power and Heating Circuits* :—By the rise in temperature which must not exceed 20° F (11·1°C).

Except for wiring fittings the cross-sectional area of any copper conductor must not be less than that of a No. 18 S. W. G. and all conductors of a cross-section

greater than No. 16 shall be stranded. The cross-sectional area of fitting wires must not be less than that of No. 20 S. W. G.

The use of single unstranded wires should generally be avoided. The most generally useful sizes for branch wiring are old 3/22, 3/21, 3/20, for sub-mains 7/22, 7/20, 7/18, 7/16, 19/8, 19/16, new standard 3/·029, 3/·036, 7/·029, 7/·036, 7/·052, 7/·064, 19/·052, 19/·064, 3/20.

Allowance for Skin Effect :—For non-magnetic wires the increase in the conductor resistance due to the so-called skin effect is 2 per cent. when the quotient—

(Cycles per sec.)$\div$(ohms per mile of conductor)$=488$.

For smaller value of this quotient, the increase of resistance due to skin effect diminishes very rapidly.

504. The Three-Wire System :—It is in a way a combination of two two-wire systems. The saving in copper by the use of high voltage, combined with practical necessity of low voltage delivery, has led to the use of the three-wire system. The middle wire of a three-wire system is generally earthed. Though the system is used for single-phase A. C. as well as for D.C., one of the outers is called +ive, the other −ive, and the fact, that single-phase polarity alternates, is ignored.

Example 3. Suppose a system with two generators, each giving 200 volts, the common terminal being earthed. The resistance of each outer is 0·013 ohms, and that of the neutral 0·026 ohms. The load is such that the positive outer carries 300 amps., the negative 240 amps. and the neutral 60 amps. A 4 per cent. drop in the voltage is allowable. Determine the distribution of the voltage.

Solution :—

Drop in + ve outer $= 0{\cdot}013 \times 300 = 4$ volts.

$\therefore$ voltage at + ve terminal of lamps $= 200 - 4 =$ 196 volts.

Drop in neutral $= 0{\cdot}026 \times 60 = 1{\cdot}6$ volts, nearly.

$\therefore$ voltage at lamps between neutral and lamps $=$ 1·6 volts

Voltage at − ve terminal of lamp

$$= -200 + (0{\cdot}013 \times 240)$$
$$= -196{\cdot}8 \text{ volts.}$$

∴ the pressure across the lamp on the + ve side $=196-1{\cdot}6=194{\cdot}4$; while on the $-$ve side it is $1{\cdot}6-(-196{\cdot}8)=198{\cdot}4$ volts; so that the available voltage at the lamp terminal on the lightly-loaded side is actually raised by the drop in the neutral.

Calculations of three-wire, direct-current circuits are made in essentially the same manner as those for direct-current, two-wire circuits. With a balanced three-wire circuit, no current flows in the neutral wire. In practice, the circuits should be very nearly balanced, and in making wiring calculations it is usually assumed that they are balanced unless there is obviously great unbalance. The first step is to ascertain the current that will flow in the outside wires. This is obtained in practice by adding together the currents taken by all of the receivers connected between the neutral and the outside wires and dividing the sum by 2 (Fig. 9·05). Then, to this value are added the currents taken by receivers, if there are any, that are connected across the outside wires. The sum is taken as the total current. The calculation is then made in the same way as for any two-wire circuit. The neutral wire is disregarded in the calculation as it is assumed that it carries no current. The neutral is frequently made smaller than the outside wires. We have circular mils$=(2\rho IL)/V$ where $\rho=$the specific resistance per mil foot $=11$ nearly for copper.

The drop in voltage V in the formula is the drop in the outside wires and is two times the drop to each receiver between neutral and outside wires. Two-wire branch-feeding from three-wire mains or feeders is computed in the same manner as for any two-wire circuit.

Example 4. Determine the size of the wire that should be used for the three-wire main of Fig. 9·05. Allowable drop is 3 volts and the distance to the load centre is 100 ft. The circuit is loaded with two groups of receivers, each taking 50 amps., connected between the neutral and the outside wires, and one group of

receivers taking 25 amps. connected across the outside wires

Solution :—

Load $=(50+50)/2+25=75$ amps:

If V=drop in volts in the circuit ;

I=current in amperes in the circuit and A the area in circular mils ;

L=length in one way or single distance of circuit in feet, we have $A=2\rho L\ I/V$.

or, cross-section $= 22 \times I \times L/V = 22 \times 75 \times 100/3$

$= 55{,}000$ cir. mils.

This corresponds most nearly to the wire No. 19/17 S. W. G , which has an area of 58,500 cir. mils. This size wire would satisfy the voltage drop requirements, but, for concealed wiring, rubber-insulated wire must be used and rubber-insulated wire has a safe carrying capacity of about 70 amps. The current in the circuit is 75 amps. Therefore, with rubber-insulated wire No. 19/·058″ should be used which will safely carry 75 amps. For interior wiring the neutral wire may be made of the same size as the outside wires, or it may be smaller. In out-of-door distribution systems the neutral is often one-half the size of the outers.

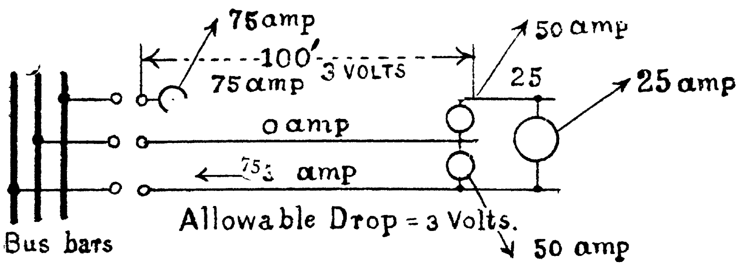


Fig. 9·05.

505. Three-Wire *versus* Two-Wire System :—
(I) Economy of Copper in Three-Wire System :— Suppose (1) the power transmitted, (2) the distance of transmission, (3) the efficiency of transmission, (4) the P. D. at the lamp terminals, are the same in both the

systems. If I=the current in the two-wire feeders, the current flowing through the outers of the three-wire feeders at double the voltage of the two-wire system is $I/2$, as the total power is the same in both the cases.

Let R_2=resistance of each wire of the two-wire system.

R_3=resistance of each wire of the three-wire system.

Since the power efficiency is the same in both the systems, the power lost in both the cases is equal.

That is, $2\ I^2\ R_2 = 2\ (I/2)^2\ R_3$

$\therefore\ R_2 = R_3/4.$

$\therefore$ the section of the two-wire feeder conductor is 4 times the section of the outer wires of the three-wire conductors, and if the three-wire system is balanced, the middle wire is generally taken to be half the section of the outers.

$\therefore$ if the two-wire system requires 100 per cent., the two outers of the three-wire system require 25 per cent., and the middle wire, being half the section of one outer, requires $6\frac{1}{4}$ per cent.

$\therefore$ the total quantity of copper required in a three-phase balanced system is 31·25 per cent. of that required in the two-wire system.

If the current density is taken to be equal in both the cases, these to carry half the current, *i.e.*, $I/2$, the section of the three-wire system is half that of the two-wire feeder system.

$\therefore$ the two outers require 50 per cent. and the middle wire 12·5 per cent., total 62·5 per cent., of the amount of copper required in the two-wire system; of course, in this the efficiency of transmission will be correspondingly increased. In out-of-door distribution system the neutral is often one-half the size of the outer wires. For interior wiring the neutral is frequently made of the same size as the outside wires. Where the outers are No. 6 or smaller, the neutral shall have the same area as the outers; but where the outers are larger than No. 6, the neutral shall have two-thirds the area of each of the outers.

(II) The current in the different parts of the neutral wire may be different, and it is not necessarily in the same direction in all parts of the neutral wire.

(III) The three-wire system, however, (*a*) is more complicated, (*b*) requires careful balancing, greater cost in joints and requires a balancer, (*c*) has greater risk of break-down. For these disadvantages the system is not adopted in short distances and small power transmission.

For continuous-current distribution, the three-wire system is almost universal, and it is sometimes used for single-phase alternating-current supply.

Note the difference between a three-wire and a three-phase system. The former is nearly a method of distribution, but in the latter system there are three absolutely distinct currents, each generated in separate winding by its own E. M. F. and each being a unit itself and capable of being used as a single-phase current and distributed, if necessary, on the three-wire system.

For distributing circuits for combined light and power, Dr. Steinmetz, in his "General Lectures," reaches the follwing conclusions in regard to copper economy :

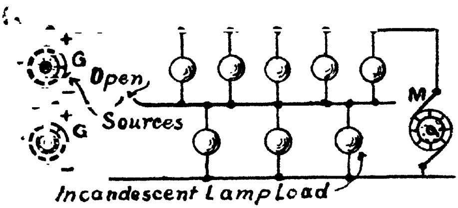
1. Two-wire, direct-current or single-phase, alternating-current, 110-volt circuit, used for short distances only, may be used as the standard of reference, and, therefore, uses 100 per cent. of copper.
2. Three-wire, direct-current or single-phase, alternating-current, 110-220-volt circuit, with neutral at half the size of outer mains will use 31·25 per cent. of copper.
3. In four-wire, quarter-phase, alternating-current circuit, each phase being 110 volts, copper used, is 100 per cent.
4. Three-wire, quarter-phase, alternating-current circuit, each leg being 110 volts, with common wire 1·41 times the size of outer mains, uses 72·9 per cent. copper.
5. Three-wire, three-phase, alternating-current circuit, line voltage 110 volts, uses 75 per cent. of copper.
6. Five-wire, quarter-phase, alternating-current circuit, with 110 volts between each line and neutral, with the neutral of one-half the size of each outer main, copper used, is 28·125 per cent

7. Four-wire, three-phase, alternating-current circuits, with 110 volts from each line to neutral, with neutral half the size of each outer main, use 29·17 per cent. of copper.

8. Four-wire, three-phase, alternating-current circuit, with 200 volts between mains, with neutral placed between two lines only forming a 110-volt, single-phase lighting circuit, with a 200-volt, three-phase power circuit, uses 31·25 per cent. of copper for lighting, but only 18·75 per cent. for power.

506. Effect of Breaks on a Three-Wire System.—(*a*) If the neutral wire opens in a three-wire circuit, the lamps on the heavier side will burn dimly or under-voltage while those on the other side will burn brighter or at over-voltage, Fig. 9·06.

Example 5. The voltage across the outers of a three-wire system is 440 and between the neutral and either outer 220 volts. The current and voltage on the positive side is 75 amperes and on the negative side 50 amperes at 220 volts. Determine the effect if the neutral is broken.



Open Neutral in a Three-Wire System.

Fig. 9·06.

Solution :—

The current and voltage on the positive side is 75 amperes at 220 volts.

∴ the resistance on the positive side is $\frac{220}{75} = 2{\cdot}93$ ohms.

∴ the resistance on the negative side $= 220/50 = 4{\cdot}4$ ohms.

When the middle wire is broken, the two sides will be thrown directly in series across the outers and

assuming their resistance to remain constant, the total resistance will be 2·93 + 4·4 = 7·33 ohms. The current will, therefore, be 44/7·33 = 60 amperes and the voltages across the respective sides will be——,

Between positive and neutral $V_p = I\,R = 60 \times 2{\cdot}93 =$ 176 volts.

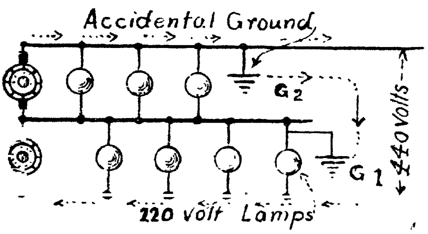
Between negative and neutral $V_n = 60 \times 4{\cdot}4 =$ 264 volts.

Hence, the lamps on one side are getting 44 volts too much and a number will be immediately burnt up; whilst those on the other side will be getting too little and will not give their full light.

This proves the necessity for maintaining the continuity of the middle wire.

(*b*) If one side is grounded and there is another ground on the opposite side of the system in a lamp connection, and if the voltage between the outers is 440, this voltage will be impressed across the lamp and it will be burnt out.

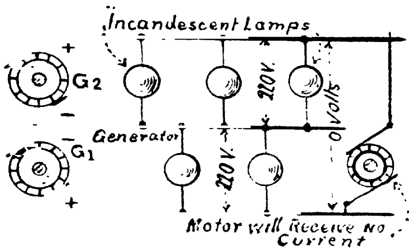
(*c*) If one of the generators of a three-wire system be reversed, the lamps, connected on both sides of the neutral wire, will receive normal voltage although their polarity will be reversed; but any motor joined with the outers will receive no current as there will be no potential drop across it.



Ground on Three Wire System Outer Wires.
Fig. 9·07.

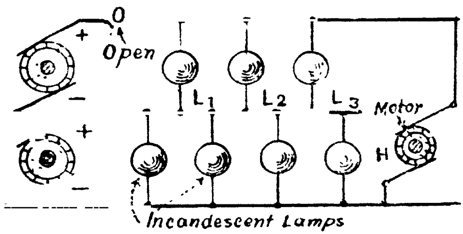
(*d*) If one of the outer wires of a three-wire system breaks, the supply to the faulty side would be cut off and the other side might be overloaded with current. There would not be any rise of pressure on the side still working. By properly joining the outers on the

distant side of the break, the lamps on the broken side will also get some current at 220 volts. But the lamps will burn dimly when so connected, as the line will not get sufficient current to operate it properly.



Reversal of Generators.
Fig 9'08.

Example 6. A circuit, having two No. 4/0 S. W. G. outer wires and a No. 0 neutral 500 yds. long, carries a load of 120 amperes on the positive side and 100 amperes on the negative side. What is the drop on each side of the circuit ?



Open in the Outer in a Three-Wire System.
Fig. 9'09.

Solution.—

The resistance of 500 yds. of No 4/0 S. W. G. $=0.195/2=0.097$ and that of No. $0=0.296/2=0.148$ ohm.

$E_P=I_PR_P=120\times 0\ 097=11.64$ volts drop on positive side.

$E_n=I_nR_n=100\times 0.097=9.7$ volts drop on negative wire.

$E_n=I_nR_n=20\times\ 148=2.96$ volts drop on neutral wire.

The drop in the neutral wire is added to the drop on the heavy side and subtracted from that on the lighter side making the total drop 11·64+2·96=14·6 volts on the heavy side and 9·7−2·96=6·74 volts on the other side.

Example 7. If, in the above example, P. D. at the generator terminals at the central station is 450 volts, and at the feeding point 2×220 volts, determine (1) the relative amounts of the copper required in the two cases, if the middle wire of the three-wire feeder is half the cross-section of the outer wires ; (2) the power lost and the efficiency of transmission; (3) the resistance of a two-wire feeder, to transmit the same power, the same distance with the same efficiency and 220 volts at the feeding point.

Solution :--

(1) Power delivered by the feeder

$=120\times220+100\times220=48{,}400$ watts.

Power received by the feeder $=\{(120+100)/2\}\times450=49{,}500$ watts.

∴ power lost=1,100 watts.

∴ efficiency $=(1-1100/49{,}500)\times100$ per cent.

$=97·7$ per cent

(2) The current in the two-wire feeder

$=48{,}400/220=220$ amps.

If the efficiency is equal, the power lost must be the same.

Now, $EI=I^2R$

∴ resistance of the feeder wire$=1{,}100/2\times(220)^2$

$=0·01136$ ohm.

(3) Let R=the resistance of the outer wire of the three-wire feeder.

Taking the maximum out-of-balance current in the middle wire to be 50 % of the current in the outer, the section of the middle wire is only half the size of the outers.

∴ the resistance of the middle wire=$2R$ ohms.

Power lost$=R\,(120)^2+R\,(100)^2+2R\,(20)^2$

$=1{,}100$ watts.

∴ $R=1{,}100/25{,}200=0·0437$ ohm.

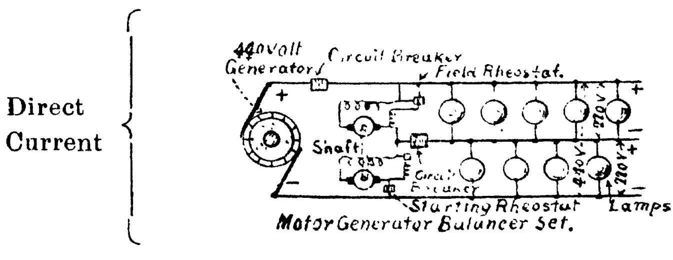
If the copper taken by two-wire feeder is 100 per cent., each wire of the circuit contains 50 % of

copper; and hence each of the outer wires of the three-wire feeder contains (0·01136/0·0437) × 50 per cent. = 13 per cent. and the middle wire, being only half the cross-section of the outers, contains 6·5 per cent. and the total copper in the three-wire feeder is 32·5 per cent.

506. Balancers.—When the power is supplied by three-wire direct current or four-wire three-phase alternate current, there is always an unbalancing of the current, between positive and negative side, in case of direct current, and between phases in the case of alternate current. The effects of this are (1) to load the different discs or phases of the system unequally making it impossible to get the full output of the lightly-loaded side without overloading the other, and (2) to make the regulation of the system worse by causing high voltage on the lightly-loaded side or phase and low voltage on the other. This out-of-balance current is dealt with by balancer sets.

The balancers are rotary as well as static. A number of balancer sets used in practice are as follows.

Motor Generator Balancer :—(Rotary) Fig. 9·10 shows a 440-volt generator in combination with a motor generator balancer. The balancer consists of two shunt-wound or compound-wound machines, each wound for half of the total voltage and having many identical characteristics. These are coupled together, each connected between an outer and the middle wire.



A 440-volt Generator in Combination with a Motor Generator Balancer Set.

Fig. 9·10.

When a system with a balancer is out of balance, the voltage on the lightly-loaded side tends to be higher than the more heavily-loaded side ; the machine with lighter load operates as a motor and drives the other as a generator. The latter then supplies current for the excess load on its side of system and thus automatically tends to balance the system. With the perfect balance of load, both the machines operate as motors running without load.

In one arrangement the field windings are connected in series across the outers (Fig. 9·11). If the system is balanced, both the machines run as unloaded motors.

If the load on one side, say, positive, is greater, the P.D. on this side falls and on the other side rises. Hence, the machine on the negative side acts as a motor driving the machine on the positive side as a generator, and if there were no loss in the machines, each would carry half the out-of-balance current. The current in the motor, however, is greater than that in the generator by the amount required to supply the armature losses.

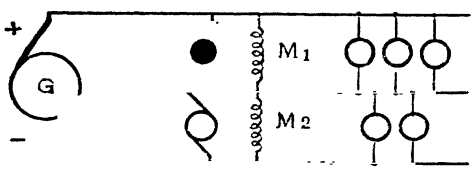


Fig 9·11.

The motor speed drops with the increase of load, and the generator voltage drops due to the decrease in speed and in excitation so that Eg is less than $E/2$.

In another arrangement by crossing the shunt coils, the regulation is much improved (Fig. 9·12).

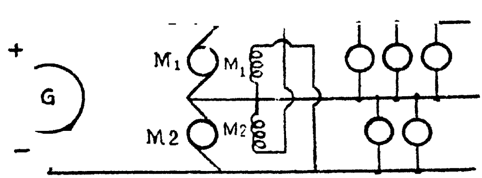


Fig. 9·12.

The fall of voltage on the heavily-loaded side weakens the field of the motor on the other side and so its speed is increased, and as the voltage

of the other side, which is lightly loaded, increases, the field of the generator is made stronger, and thus the balance is secured more closely.

In compound-wound machines (Fig. 9'13) the series windings are connected in series with the middle wire in such a way that the field of the machine on the loaded side is weakened, while that on the other side is strengthened ; in other words, the generator field is increased and the motor field is weakened, or the generator is cumulatively compounded and the motor is compounded differentially, no matter in which direction the unbalanced current flows ; and as a result, the increase of speed and speed excitation of the machine on the loaded side, causes it to supply the extra current required. By using a suitable number of series turns the voltage can be exactly balanced at full out-of-balance load. By suitable adjustment of the load the out-of-balance current is made as small as possible and usually about 10 per cent. of the total output so that the rated capacity of each of the machines does not exceed 10 per cent. of the entire capacity of the plants. A dynamotor having two windings on one armature and two commutators may be also used to balance the currents by joining the armatures in series, but the voltages cannot be balanced as there is only one field.

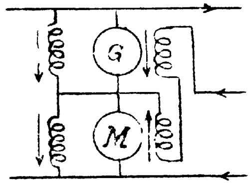
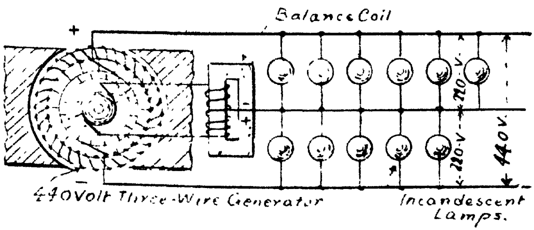


Fig. 9'13.

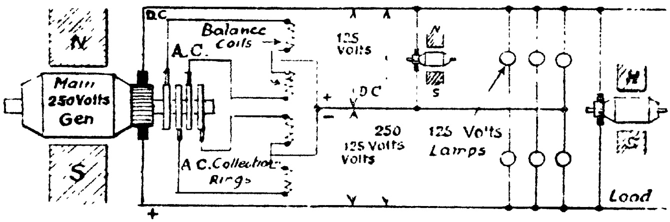
Three-wire Generator With a Balancing Coil :—In



Three-Wire Generator.

Fig. 9'14.

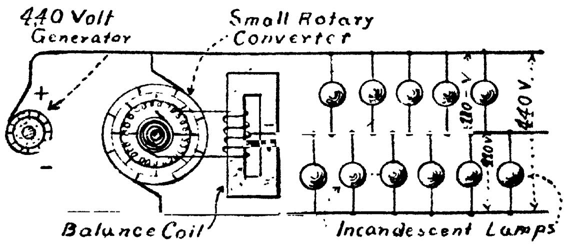
this, the generator is designed for the maximum voltage between the outers having collector rings connected to the armature like two-phase converter. The leads from the collector rings are connected to a balancer coil, as shown in Fig. 9·14, or to an auto-transformer. The neutral wire is connected to the middle point of this balancing coil. This automatically balances the out-of-balance current without any other rotary device.



A 250-volt three-wire generator. It has four slip-rings connected to four equidistant points of the armature winding as rotary converter. The balance coils are connected as in the quarter-phase system.

Fig. 9·15.

Motor Converter Balancer :– In this a small rotary converter is used as a balancer. The leads from the



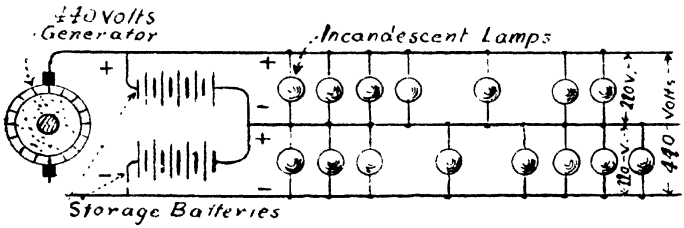
A 440-volt Generator in Combination with a small Rotary Converter used as a Balancer.

Fig. 9·16.

slip-rings are connected to a balancing coil as in the previous case. The neutral is taken from the middle point

of this balancing coil. Fig. 9·16 shows a 440-volt generator in combination with a small rotary converter used as a balancer.

Battery Balancer :—This consists of a set of storage batteries on both sides of the neutral when the voltage between the outers is equal to the charging voltage of the two batteries connected in series (Fig. 9·17). The neutral wire is taken from the middle point of the connection of the two batteries. It is identical with the two direct-current generators connected in series. If the load on one side of the neutral is heavier than the other, the voltage on that side will be lower than on the lightly-loaded side. The unbalanced current on the heavily-loaded side will be supplied by the battery on that side. The battery on the lightly-loaded side will be charged at the same time.

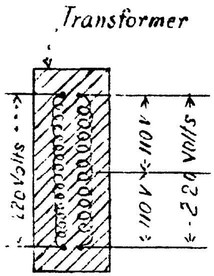


A 440-volt Generator in Combination With Storage Battery Balancers for Obtaining Three-Wire Voltage.

Fig. 9·17.

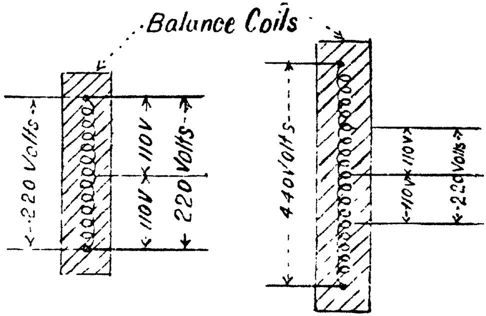
Balancing in Alternating Current Circuit :—The neutral in single-phase two-wire system is usually obtained from the middle point of the coil of the transformer supplying the current. By the use of balance coil—a transformer with two similar windings connected in series across the circuit with the neutral wire connected to the common point between the windings—the neutral point can be obtained at any point of the two-wire circuit. The coil which is on the lightly-loaded side, acts as the secondary, thereby balancing the circuit by

transferring one-half of the difference in load from the



Transformer
balancer

Fig. 9·18



Auto-Transformer of
Balancer Coil

Fig. 9·19

heavily-loaded side to the lightly-loaded side. In practice, however, balance coils are not much used as the neutral can be more cheaply obtained from the transformer.

Capacity of Balancer :—5 per cent. is a fair average for a well-laid balanced system. But balancer sets for interior three-wire system are frequently specified of sufficient capacity to take care of 10 per cent. unbalance, as in such system the unbalanced load seldom exceeds 10 per cent. of the total load. Sometimes it is even 20 per cent., or even more.

Balancer Formulæ :—The following equations give the current taken by the motor and that given out by the generator during unbalancing.

$I_g = I_o \dfrac{\eta_m \times \eta_g}{1 + \eta_m \eta_g}$, where I_g is the generator current.

$I_m = I_o \dfrac{1}{1 + \eta_m \eta_g}$, where I_m is the current taken by the motor.

The efficiency η in each case is given with the shunt excitation loss neglected. The actual combined efficiency is given as—

$$\text{Efficiency} = \frac{I_g}{I_m + 2i}$$

Note.—The efficiency is negative when the load is nearly balanced, for then both machines operate as motors. As unbalancing increases, the efficiency gradually rises to zero and then becomes positive; or the losses in the balancer set increase the output of the main generator above the useful demand for power. The ratio of this demand to the output of the main generator may be called the efficiency of the three-wire system with reference to the balancer.

507. Booster.—It is a generator, driven by a motor or otherwise, inserted in series in a circuit, to change its voltage. It carries large current at low voltage, has long commutators in proportion to their output. When driven by an electric motor, it is termed 'motor booster.'

Use.—(1) To compensate for the pressure drop down a feeder supplying power at a distance.

Feeder Booster :—The drop in a feeder can be compensated and the bus-bar voltage can be supplied at a distant point by a booster, as shown in Fig. 9·20, capable of generating an E. M. F. equal to the drop down the feeder and of carrying the maximum current supplied in series with the feeder.

For automatic action it should be series-wound when the entire current of the feeder passes through ; but if shunt-wound booster is used, the booster is regulated by adjusting the field rheostat by the attendant. It is usually driven at constant speed by a shunt motor. It is necessary that the booster is run at normal speed by means of the driving motor before it is thrown in series with the feeder and the driving motor must not be shut down when the booster is no longer required before the

two-way switch has been thrown over to cut out the booster.

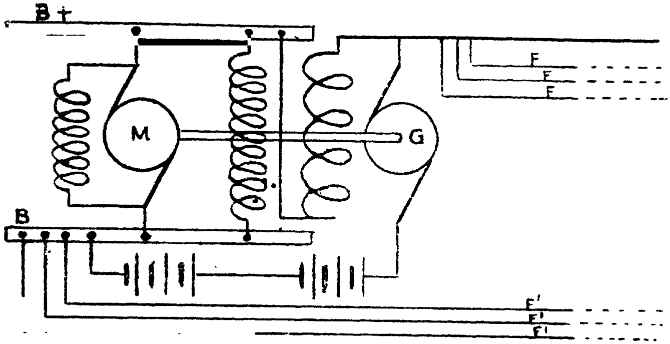


Fig. 9·20

(2) *To charge or discharge a battery* when its voltage is above or below that of the bus-bars, see Art. 322.

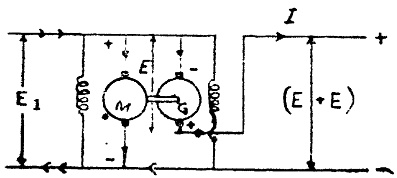


Fig. 9·21.

The generator has two separate windings; the series-winding carries the load or generator current or a part of it and tends to excite the generator so that it helps the battery in discharging. The other, a shunt-winding, carries a nearly constant current opposing the magnetising effect of the series-winding.

For a certain value of the current through the field coils the ampere-turns are equal in the field magnet and then the generator produces no E. M. F., but when the load increases, the series coil preponderates over the shunt and helps in the discharge of the battery and reduces the load on the generator, and conversely when the load decreases, the battery is charged by the generator which is helped by a suitable booster.

Example 8. A trolley is supplied with power by a generator at 550 volts. The line is 3 miles long and

consists of No. 00 S. G. W. wire having a resistance of 0·453 ohm. per mile. The rail return has a resistance of 0·04 ohm per mile. A feeder line, consisting of three No. ·00000 S. W. G. wire resistance=0·098 ohm. per mile, extends from the station for a distance of 2 miles on the trolley line. The booster voltage is maintained at 50. Determine the voltage on a car as it travels from the line towards the station, assuming the current taken to be always 250 amps.

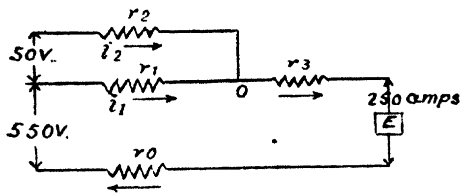


Fig 9·22.

Solution.—

First, suppose the booster to be disconnected when car is at the distant end.

Drop in trolley wire$=250 \times 0·453 \times 3=339·75$ volts.

Drop in rail$=250 \times 0·04 \times 3=30$ volts.

$\therefore$ voltage on car without booster$=550-(339·75 + 30)=180·25$ volts.

This shows that the regulation of the line is to be improved ; hence the necessity of a feeder line.

Now, suppose the booster is to be connected. Denote the voltage on the car by E, and the currents in the line by i_1, i_2,...and the resistances by r_1, r_2,..... , as indicated in Fig. 9·21, the arrows show the arbitrary directions of current

By Kirchhoff's Laws :—

$$i_1 + i_2=250 \quad \ldots \quad (1)$$

$$i_2 r_2 - i_1 r_1 = 50 \quad \ldots \quad (2)$$

$$i_1 r_1 + 250\, r_3 + E + 250\, r_0=550 \quad \ldots \quad (3)$$

Where $r_1 = 0·453 \times 2 = 0·906$ ohm, $r_2 = 0·098 \times 2 = 0·196$ ohm

$r_3=0·435$ ohm, and $r_0= 0·04 \times 3=0·12$ ohm.

From equations (1) and (2) :—

$i_2 = (250\, r_1 + 50)/(r_1 + r_2)=(250 \times 0·906 + 50)/(0·906 + 0·196)=251$ amps.

$i_1=250-251=-1$ amp.

Hence, from equation (3) we have—

$E = 550 + 0{\cdot}906 - 113{\cdot}25 - 30 = 407{\cdot}66$ or 408 volts (approx.). Thus there is a total drop of 142 volts instead of 370 volts without the booster.

Let the car be now at O, the point where the feeder is connected to the trolley line.

Equation 3 now takes the form—

$i_1 r_1 + E + 250\, r_0 = 550$;

and $r_0 = 0{\cdot}04 \times 2 = 0{\cdot}08$ ohm.

$\therefore E = 550 + 0{\cdot}906 - 20 = 530{\cdot}906$, or 531 volts (approx.).

Again, when the car is at a distance of 1 mile from the generator, the equations above become :—

$$i_1 + i_2 = 250 \quad \ldots \quad (1')$$
$$i_2\,(r_2 + r_1/2) - i_1 r_1/2 = 50 \quad \ldots \quad (2')$$
$$i_1\, r_1/2 + E + 250\, r_0 = 550 \quad \ldots \quad (3')$$

r_0 being now 0·04 ohm. only.

Solving i_2 gives—

$$i_2 = (125\, r_1 + 50)/(r_1 + r_2) = (113{\cdot}25 + 50)/1{\cdot}102$$
$$= 148 \text{ amps.}$$
$$i_1 = 250 - 148 = 102 \text{ amps.}$$

Therefore, from (3′) —

$$E = 550 - 102 \times 0{\cdot}453 - 250 \times 0{\cdot}04$$
$$= 493{\cdot}794 \text{ or } 494 \text{ volts (approx.)}$$

This shows clearly that by the simple connection of the booster to a point chosen more or less at random on the line, the voltage of the line becomes more nearly uniform than it would be without the booster.

* 508. Testing for Faults in Circuits.

1. *A short circuit* is located to one circuit by the blowing of the fuses in the particular circuit in which the short circuit occurred and its exact position is indicated by a bad lamp, a fallen lamp-holder, broken flexible at ceiling rose, etc., and at sharp bend. It takes place from cable to cable through the conduit and is generally located at joint boxes, connectors, etc.

2. *An open circuit* is located to a small section of a circuit when a lamp will not light up, or some motor will not start on closing the switch.

* W. S. Ibbetson's Electric Wiring.

3. *A leakage* is usually located in a similar way to an earth or by some particular fuse blowing. Leakages and earths are often caused by a general dampness of numerous fittings and lengths of conduit. Cleaning of all accessible parts will often improve a circuit considerably, specially when it appears impossible to locate exactly the position of leakage. All leakages are connected in parallel with each other. The more leakages there are, the lower will the insulation resistance of the whole installation become.

4. *Testing for Earth Faults.*—This is usually done by :—

(1) the lamp detector ... } on live circuits.
(2) the voltmeter ... }
(3) megger or ohmmeter and generator - on dead circuits.

Indication of Earth Fault by Voltmeter :—Suppose an earth exists in a fitting in a house ; if the wire thus in contact with the fitting was the positive wire, anyone touching the bare negative main would get a shock. If a voltmeter was connected to the positive main and earth, there is no difference of potential between them, and the voltmeter would register zero potential difference. If one terminal of the voltmeter was connected

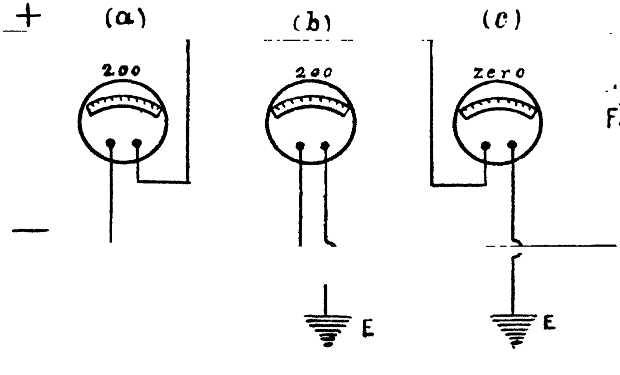


Fig. 9·23.

to the negative main, and the other terminal to earth, since the earth is at the same potential as the positive main, and the two mains have a P. D. of, say, 200 volts, the voltmeter would indicate this voltage between negative main and earth. The main, to which the voltmeter is connected, and which shows full voltage when connected to earth through the instrument, is not the faulty main. The earth is on the other main, which records a very small or zero voltage reading, (*a*) shows the voltmeter connected across the two mains, showing the full voltage, (*b*) shows the same voltage reading, the circuit being completed through the earth and fault, (*c*) shows the voltmeter connected to the faulty cable and earth, no P. D. being indicated. In the illustration given there would be no leakage of current although an earth is present, since the current, although it has a free path to earth, has no path whereby it can get back to the dynamo by means of the negative main. The insulation of the system is, however, weakend by half, and a breakdown takes place if any weak place occur in the insulation of the negative cable, as there is a pressure equal to the full pressure of the circuit upon it and results in a short circuit between the two mains, and the blowing of the fuses in the circuit, etc.

In small installations, earth the opposite main to that on which the fault is by a piece of cable. A large current flows across the short circuit thus produced, resulting in the burning out of the cable at the fault. The fault can then be often easily located by the smell of burnt insulation or perhaps the refusal of lamps to burn beyond a certain point. This is a dangerous method.

*** 509. Testing the Insulation of a Whole Installation or a Sub-Circuit to Earth by the Megger Testing Set.**—The test of a whole installation :—It should be made from the position at which the Supply Company's main D. P. switch connects up the supply mains with the customer's mains.

Proceed over the whole of the installation, put on all switches, put in all fuses.

Connect the "earth" terminal of the megger to a water-pipe or good earth connection.

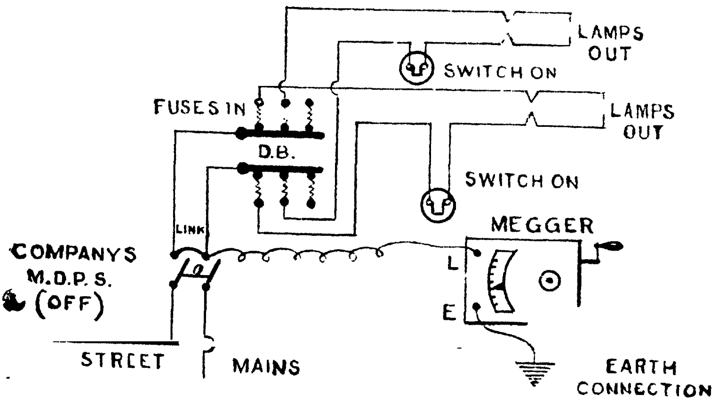
Test the earth connection by touching some part of the conduit with the "live" wire of the megger and see if the pointer flies back to zero; if it does not fly back on a slight turn of the handle, the earth is not a good one.

Now turn the handle, with the line connected to the two ends (+ve and −ve) of the customer's main leads linked together. Turn the handle fairly vigorously, but not rashly, and note the indication of the pointer on the scale.

$$\left.\begin{array}{l}\text{Insulation in megohms must be}\\ \text{either equal to or greater than}\end{array}\right\} 30/\text{ Number of points.}$$

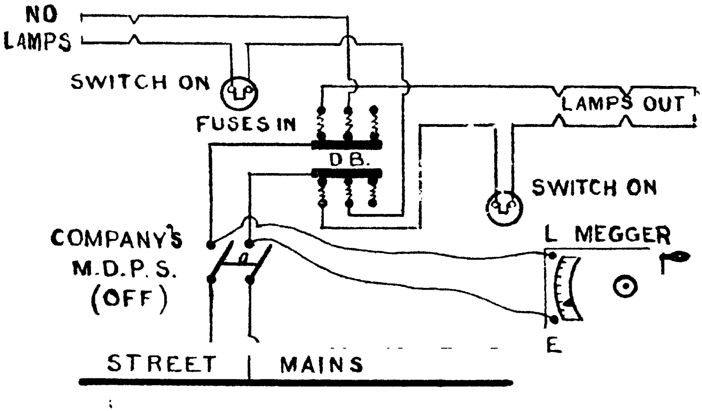
The test to earth of any part of a circuit may be made in exactly the same way from any fuse-board. The fuses of the circuit to be tested are taken out at the board, and the test made from the two cable connections, as in the case described above.

Fig. 9·24 shows the connections required to test the total wiring of a premises for insulation to earth.



Method of making an insulation test to earth by means of the Megger testing set, before connecting to the supply mains.

Fig. 9·24.



Method of making an insulation test between cables of opposite polarity by means of the Megger testing set.

Fig. 9·25.

A zero reading would indicate a short circuit between the two cables.

Testing Insulation between Cables of Opposite Polarity :—Disconnect the lamps in the circuit, put all switches on and all fuses in position. Join the "earth" of megger to one cable and the "line" to the other. Read the indication of the pointer, in order to get the resistance between cables. To test connections, insert one lamp anywhere in circuit, the pointer of the megger should fly back to zero.

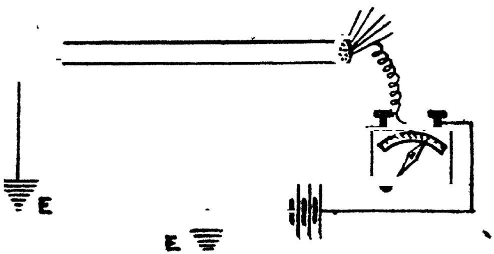


Fig. 9·26.

Fig. 9·26 shows one method for testing cables.

510. I. E. E. Rule for Insulation Testing after completion before Current may be switched on:—The whole of the lamps having been connected to the conductors, and all switches on, and fuses being in position, a pressure equal to twice the working pressure must be applied, and the insulation resistance of the whole or any part of the installation must not be less in megohms than 25 divided by the number of lamps. When all lamps and appliances have been removed from the circuit, *the insulation resistance between conductors must not be less than 25 megohms divided by the number of lamps. The insulations of any individual sub-circuit must not fall below 1 megohm.* Any motor, heater arc lamp, or other appliance may be connected to the supply of electrical energy provided that the insulation of the parts carrying current, measured as above, is greater than 1 megohm from the frame or case.

511. Methods of Fault Location:—There are various methods of locating fault. A number of them are described in the following articles. The method to be adopted in any given case will depend upon the nature of the fault, for one of the following methods may be more convenient and useful for one type of the fault than for the other.

It is not advisable to begin to apply one of the methods to locate the fault at once, for it is possible many a time, to find out the exact spot of fault by means of some simple preliminary tests. In case of a fault, it is necessary to find out the exact position of the underground cable from the map of the network which is always with the mains Assistant. After that, it is a common practice to find out how much area is affected, and then to walk in the direction of cable to find out any hot spot or some smell of burning insulation, if possible. If this method does not succeed, it is essential only to apply any one of the following tests.

512. Voltmeter Method of Locating Faults:—(on live mains)—Suppose at a time of light load on disconnecting the switches in the central station, the

attendant finds that the earth goes off or the leakage to earth is considerably diminished, when one particular feeder switch is out. The earth occurs on this feeder, proceed to the first distribution centre along the route of this feeder. At the distribution centre, which consists of a D. B. with fuses connecting up the sub-circuits, test the two live main cables leading back to the bus-bars by means of voltmeter, test each main separately to earth and see whether the fault is on these mains or not. Put in the fuses connecting up the distributing mains and test the board as such set of fuses is replaced. On replacing one particular set of fuses the voltmeter will register the full voltage fall to earth, showing that the fault is on the mains connected to the feeders by that particular set of fuses. Now go to the separate M. D. Bs. inside the customers' houses, along the route taken by these distributing mains. Disconnect one particular board and test the live mains back to the distribution centre, the earth goes off when the fault is located on this system connected to this board. If there were service pillars along the route, he would take out the fuses until he found which premises the fault was on, and then proceed as described. Take out the fuses at the M. D. B. until, on taking out one set, the earth reading goes off. Insert the fuses again and trace the particular circuit to the smaller fuse board. The same procedure is gone through, and the small lighting circuit is located when on disconnecting this circuit the fault goes off.

Having located the "earth" to one small circuit, the tester must first examine the fittings which are easily got at and replaced, such as lamp-holders, ceiling roses, connection boxes, for signs of arcing, smell of burning, etc. Failing to find any signs of the fault he will now proceed to examine the parts more difficult of access, such as inspection bends and boxes, and if he is still unsuccessful, he must now split up the circuit at these points into as small sections as possible, and test each part thus obtained by means of the megger separately. Finally, he will discover the length of cable on which the fault is, and by means of it, pull in a new cable in

its place. As mentioned previously, a general wetness may result in a very low test, and the mere cleaning and drying of fittings, better ventilation, or draining of conduit, etc., may result in cleaning general faults, what cannot be located, to one particular point.

513. Lamp Detector for Earth Testing.—(Live Circuits.)—One terminal of the lamp, which is made to burn on the voltage of the circuit under test, is connected to the + ve or — ve cable and the other terminal to earth. Where the voltmeter would show a drop equal to the full voltage of the circuit, the lamp would burn brightly; where no voltage drop is shown on the voltmeter, the lamp would remain unlighted. If the drop was not that of the full voltage, the lamp would, perhaps, burn dull red. Exactly the same procedure is taken in testing with lamp as with the volt-meter; the tester proceeding from one D. B. to another until the circuit on which the fault exists is located.

514. To Test an Installation after Completion for Continuity, Insulation and Short Circuit:—

(1) Continuity Test.—Disconnect the circuit which is required to be tested at a fuse board and with all the lamps in and switches closed; connect the two ends of the circuit to the "earth" and "line" terminals of the megger. When the handle is turned the needle will be jerked to zero mark, if the circuit is continuous. Connect the circuit to the mains, and close the switches, the lamps in the circuit will burn. If there is a broken circuit somewhere in the flexible or other lamp connection or fitting, the lamp in the circuit fails to burn. This can be remedied easily.

(2) Testing of an Installation for Insulation Resistance to earth (I. E. E. Rules). The insulation resistance of an installation should be subjected to separate test before it should be connected to the supply.

First it should be tested when wiring is complete but no fittings or appliances are connected to it. Secondly, when all the lamps and fittings are in position and connected up. The insulation resistance to earth of the whole or any part of the wiring, must, when tested

previously to the erection of fittings and electroliers, be measured with a pressure not less than twice the intended working pressure, and must not be less in megohm than 30 divided by the number of points under test. For this purpose the points are to be counted as the number of terminal wires from which it is proposed to take current, either directly, or by flexibles, to lamps or other appliances.

In the Government installations in India the rule is that when tested at double the working pressure (subject to a limit of 500 V) the insulation resistance to earth and also the insulation resistance between poles shall not be less than (25 megohms number of points wired). Any motor, heating appliance, arc lamps, etc. together with its control gear or their accessory apparatus, must have an insulation resistance on the live parts of not less than one meghom from the frame or case, or the leakage current must not exceed $\frac{1}{5000}$ part of the maximum current demanded on the consumer's premises.

In the case of lighting circuits, the whole of the lamps having been connected to the conductors and all the switching being on and fuses in circuit the insulation resistance of the whole or any part of the installation must not be less in megohms than 25 divided by the number of lamps.

Example 9. Suppose a circuit supplied 4 wall brackets, a four-light pendant and 3 wall-plug sockets. The total points are $4+1+3=8$. The insulation resistance of such a circuit must$=30/8=3{\cdot}75$ megohms, at least, before it will be considered satisfactory.

515. Notes on Testing.—(i) Take great care while connecting any instrument to proper "earth"—rusted or painted iron pipes are often not earthed. A water-pipe is the best earth that can be usually obtained.

(ii) Do not cut a cable for testing purposes. It is quite certain that it is necessary and the deductions from the test are reliable. Sections of circuits are cut out by fuses, cut-outs, and switches.

(iii) Faults are often found in joints (and the jointer) and sharp bends.

(iv) Determine the reason and then remove the cause. If it blows because the current is too heavy replace it by a larger size.

***516. The Volt-Ammeter Test**.—In this method a second unfaulted conductor between the testing stations is used to serve as a potential lead to the far end of the faulted conductor.

In Fig. 9·29 *dc* represents the faulted wire, and *ab* the unfaulted wire ; then, if V_1 is the reading of the voltmeter, and R_v the voltmeter resistance, the P. D., V_x, between the ends of x, is given by,

$$V_x = V_1 \left(\frac{R_v + r}{R_v}\right).$$

Again I_1 is the reading of the ammeter, the current

through x will be $I_x = I_1 - \left(\frac{V_1}{R_v}\right)$.

To eliminate r when it is an appreciable fraction of R_v; transfer the ammeter connection to a and make a second observation. Let V_2 be the reading of the voltmeter and I_2 that of the ammeter. Then, the voltage across the ends of r is given by,

$$V_r = V_2\ (R_v + x)/R_v$$

and the current through r is $I_r = I_2 - V_2/R_v$. In Fig. 9·30 we get voltameter method for fault location with an ammeter inserted between B and E. From the above four equations the value of x is easily found to be

$$x = \frac{V_1}{I_1 - \frac{V_1}{R_v} - \frac{I_1}{I_2} - \frac{V_2}{R_v}}.$$

With an electrostatic voltmeter, no allowance is necessary for the voltmeter current, and x is directly given by $x = V/I$.

517. The Loop Test.—This is generally the last and most used method of locating a fault. The advantage of the loop is: that the results are independent of the

fault itself. The test is carried out by determining the resistances of the two portions of the loop formed by connecting the faulty conductor at its far end to an unfaulted conductor which returns to the sending station. This is shown in Fig. 9·27; ab is the faulty conductor, the fault being at b'; dc is the unfaulted conductor, and is connected at its far end to the faulted conductor by a low-resistance jumper which must be insulated from ground. The contacts b and c must be perfect.

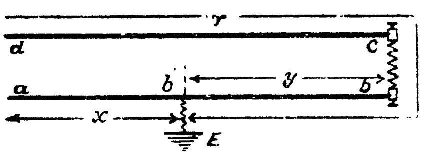
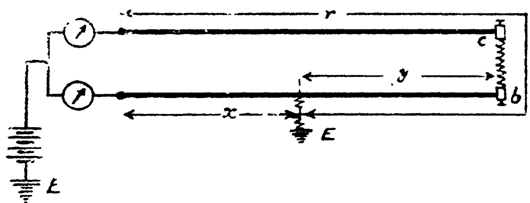


Fig. 9·27.



Loop Test Locating Faults.

Fig. 9·28.

***518 Two-Ammeter Loop Test.**—In this method the two sections of the loop are connected in parallel to the same battery and the ammeters are placed in series with each branch,—one in series with x and the other in series with r as shown in Fig. 9·28. The polarity of the battery should be such that the fault resistance is a minimum. In calculation the two ammeters and the connections are assumed to have negligible resistances. If I_x and I_r are the readings of the ammeters,

$$I_r/I_x = x/r, \text{ or } I_r/(I_x+I_r) = x/(x+r)$$

$$\therefore x = (x+r)\,[I_r/(I_r+I_x)] \quad \ldots \quad \ldots \quad (1)$$

The total resistance of the loop, $(x+r)$, may be determined by the volt-ammeter method.

Formula (1) gives the resistance of the faulty conductor from the sending end to the fault. If the conductors are both of the same material and size, the resistance per unit length will be the same for both at the same temperature. Hence,

distance to fault = total length of loop $\times$ $[I_r/(I_r + I_x)]$.

Similarly, the resistance, y, from the far end of the conductor to the fault may also be obtained, for

$$I_x/I_r = r/x,$$

or

$$(I_x - I_r)/(I_x + I_r) = (r-x)/(r+x)$$
$$= \{(r-x)/2\}/\{(r+x)/2\}$$

Hence, for a loop of uniform resistance per unit length, distance from far end of line to fault =

length of one wire $\times$ $(I_x - I_r)/(I_x + I_r)$.

Nicholson applied this two-ammeter method for locating broken or defective insulators on long high-voltage A. C. transmission lines. Most of the methods of fault location are rendered impracticable here in as much as the voltages must be so high, that the defective insulator may arc over to the metal supporting pin and thus establish the fault. In fact, full-line voltage is often required for this test.

This method was first tried on a plant which transmits power at 60,000-volts, 25-cycles, 3-phase, over lines 160 miles long. The transformers are operated with a grounded neutral. The insulator pins are also grounded. Consequently, any breakdown of insulators at once establishes a short circuit, and the trouble must be rectified, before service can be resumed. It is desirable that special apparatus be avoided.

The arrangement is shown in Fig. 9·29. The three disconnecting switches A′, B′, C′, are opened at the far end of the line. At the near end, the disconnecting switches in A and B are opened and both ends of the line are connected by means of jumpers as shown.

R is a rheostat arrangement for controlling the current after the arc to ground has been established. An expulsion fuse is inacted at *F* which short-circuits *R*.

This allows the voltage at the fault to be raised high enough to start the arc and then blows, throwing in the controlling resistance R. The controlling resistance consists of four concrete columns 1 foot-square and 12 ft. long with expanded metal terminals, each having a resistance of about 2,000 ohms, and may be used either singly or in parallel as occasion requires. A current of 50 to 100 amperes is required for the test. In cases where the striking distance is several inches, the testing current may be kept on for 30 to 40 seconds without burning the aluminium conductors. This allows sufficient time for taking the ammeter readings.

If a single size of conductor is used, the currents divide inversely as the resistances of the two paths, and so formula (1) is applicable.

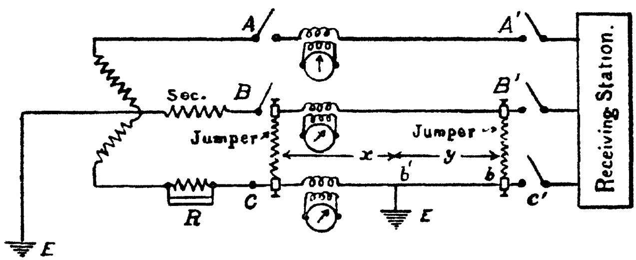


Diagram for Nicholson's application of the two-ammeter loop test to high-voltage lines.

Fig. 9·29

•519. Murray Loop Test.—In this test the connections are made as shown in Fig 9·30. The resistance x and r of the loop form two arms of a Wheatstone Bridge, the other two arms being made up of resistances under control of the observer.

The relative positions of the galvanometer and battery are important. With the connections as shown, earth currents have no effect on the readings.

When balance is obtained,

$$A/B=r/x \text{ or } (A+B)/B=(r+x)/x.$$

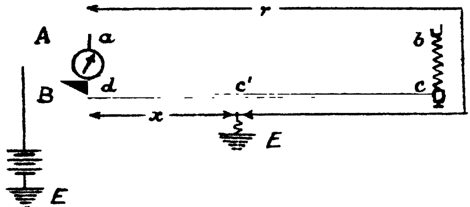
$$\therefore\ x=(r+x)\ \{B/(B+A)\}$$

The total resistance of the loop $(r+x)$ is obtained by a bridge measurement.

If the wires are uniform,

distance of fault=total length of the loop $\times \{B/(A+B)\}$. Take a potential divider or a side-wire bridge with extension coils for $A+B$, where $A+B$ is constant.

If a cross occurs between two conductors in a multiple-conductor cable it is located in a similar manner. In this case the battery, instead of being connected to ground, is attached to one of the two faulty wires, the other being looped with an unfaulted wire.



Connections for Murray Loop Test for fault location.

Fig. 9·30.

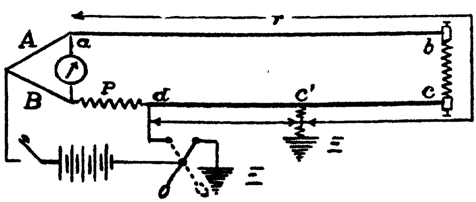
***520. Varley Loop Test.**—In this, use a fixed bridge ratio and obtain the balance by adding resistance to the smaller section of the loop.

When the apparatus is arranged as in Fig. 9·31 with the switch in the given position, and the balance is obtained,

$$A/B=r/(x+P_1),$$

P_1 being the resistance unplugged at P,

or $$x=\{(x+r)B-P_1 A\}/(A+B)$$



Connections for Varley Loop Test for fault location

Fig. 9·31.

The total resistance $(r+x)$ of the loop is measured by throwing the key to the dotted position and obtaining a second balance using the apparatus as an ordinary Wheatstone Bridge.

521. Fisher Loop Test.—In this method of testing, there must be two unfaulted wires, which run from the testing station to the far end of the line.

Two balancings are necessary, as indicated in Fig. 9·32.

From the first balance

$$A/B=(Z+y)/x.$$

From the second balance,

$$A'/B'=Z/(x+y).$$

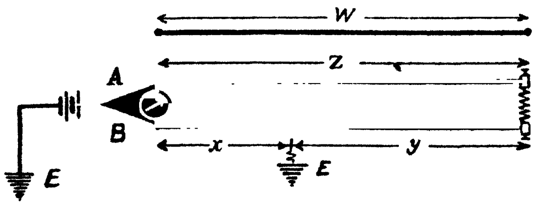
Hence, $$x=(x+y)\,\frac{\dfrac{A'}{B'}+1}{\dfrac{A}{B}+1}$$

If a slide wire or its equivalent is used for the balance arms, $A+B=A'+B'$ and

$$x=(x+y)\;B/B'.$$

If the resistance per unit length of conductor is uniform,

$$\text{distance to fault}=\frac{\dfrac{A'}{B'}+1}{\dfrac{A}{B}+1}\times(\text{length of cable}).$$



Connections for Fisher Loop Test for fault location

Fig. 9·32.

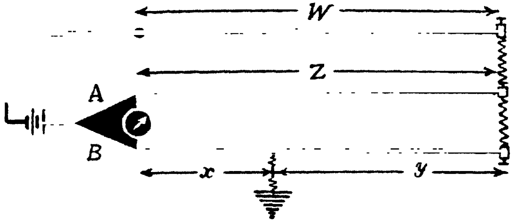


Fig. 9'33.

522. "Cut and Try" Method of testing cable:—This method is usually applied when the other methods nearly fail and when the cable is to be put into service again at the earliest possible moment at any cost. In the case of a "distributor" or a "service line," the first cut is made at the central point of the run (provided the fault is suspected at the particular point from the stoppage of supply). Then the megger test is applied at each side of the cut and the faulty side is detected. The second cut is made at the centre of the run of the faulty side and again the "zero test" is applied with megger. The process is repeated till the fault is located.

Note:—Before applying the megger, it is necessary, to find out with the test lamp whether the cable is dead or not.

523. Induction Method:—This is also known as Sharman's Test. The great advantage of this method is that no knowledge of the resistance of the cable under test is required and therefore the uncertainty due to partial breakdowns and bad joints do not affect it. It can also be applied when there are several "earth" faults on the cable. The figure opposite shows the connections. Suppose the cable L. M. is "earthed" at F. The end M is isolated (taken out from the bus-bar at Feeder pillar.) The other end L. is connected to one terminal of the secondary of a portable transformer. The other end of the secondary is "earthed." Current flowing from the battery to the primary of the transformer through the "make and break" switch, sets up a fluctuating flux in

the secondary. This passes on to the core in cable, up to the point, where it is "earthed"; beyond the point there is no flux. A search coil (triangular shape is most convenient; say 3 ft. side and wound with about 200 turns of between 26 and 30 S. W. G. insulated wire), the terminals of which are connected to a telephone receiver, is then carried along the roadway above the cable, the plane of the coil being parallel to the cable. If there is a fault on either the neutral or the unearthed outer, the beats will be heard corresponding in frequency to the movement of the interrupter. These beats will continue right up to the location of fault and on passing this point they will cease. Thus the point of fault can be exactly located.

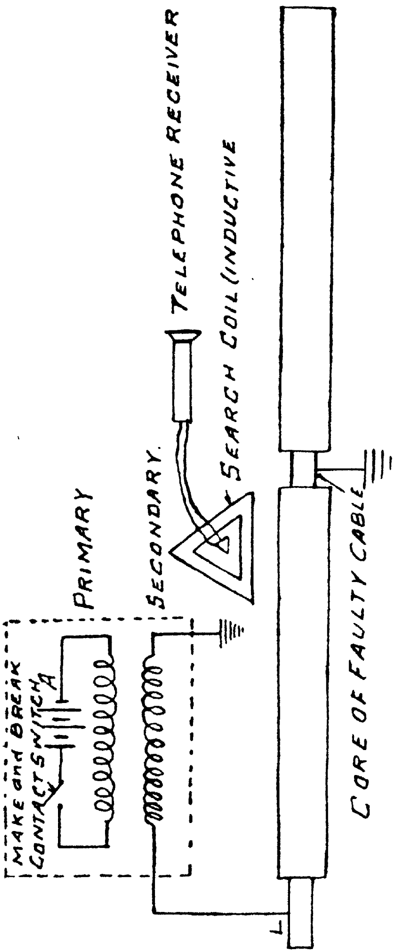


Fig. 9·34.

The accuracy of this method can only be relied upon where the cable sheathing is non-conducting. Where there are gas and water pipes, or led-sheathed or armoured cables adjacent to the faulty cable, the leakage current may flow along them in unexpected directions and unless care is taken, misleading results may be obtained.

*** 524. Determination of the Total Resistance of the Defective Conductor, Case** (1).—With a single perfect wire between the stations it is not possible to find the total resistance of the faulty conductor by measurements made from one end of the line.

The determination can, however, be made by tests from both ends of the line. First, the line is looped at B with the unfaulted wire with Z (Fig. 9·35), and x is determined by one of the previous methods. Then, the loop is made at A, and y is determined in a similar way by observations from the end B. The total resistance is obviously $(x+y)$.

Case (2)—With two perfect wires between the stations, observations from one end of the line will suffice. In a multiple-core cable, two unfaulted wires, in the same cable, may be used as the auxiliary, wires (see Fig. 9·35).

Method I.—The faulty wire is first looped with Z and the resistance, R_1, of the loop determined by a bridge thus :—

$$R_1=(x+y)+Z.$$

Then, loop the faulty wire with W, and find the resistance, R_2, of this loop thus :—

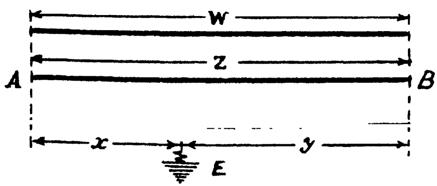
$$R_2=(x+y)+W.$$

Lastly, loop W and Z and measure the resistance, R_2, of the loop thus :—

$$R_3=W+Z.$$

Then

$$(x+y)=R_1+R_2-R_3/2$$



Determination of Resistance of Faulty Conductor.
Fig. 9·35

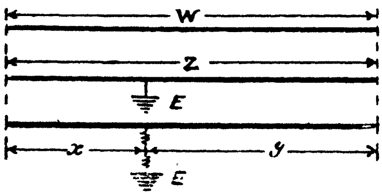
* Law's Electrical Measurements.

Method II.—The faulty wire is looped with Z and the loop resistance, R_1, measured as above thus :—

$$R_1 = (x+y) + Z.$$

Next, W and Z are looped and grounded at B, and Z determined by one of the previous methods ; then

$$(x+y) = R_1 - Z.$$



Determination of Resistance of Faulty Conductor.

Fig. 9·36.

When there are one perfect and two faulty wires of equal length and resistance between the stations, (Fig 9·36), the total resistance of either of the faulty wires may be determined as follows :—

Loop Z with W and determine the resistance, R_1, of the loop. Loop $(x+y)$ with W and determine the resistance, R_2, of this loop. Finally, connect Z and $(x+y)$ in parallel and loop the combination with W, and determine the resistance, R_3.

Then,

$$R_1 = Z + W.$$

$$R_2 = (x+y) + W.$$

$$R_3 = W + Z\{(x+y)\}/\{(x+y)+Z\}.$$

Whence,

$$(x+y) = (R_2 - R_3) + \sqrt{(R_3 - R_2)\ (R_3 - R_1)}$$

or,

$$Z = (R_1 - R_3) + \sqrt{(R_3 - R_2)\ (R_3 - R_1)}$$

If the ratio of the resistance up to the fault to the total resistance of the conductor be made equal for both the defective wires, then there will be no flow of current through the faults. This principle is made use of, when strict accuracy is observed.

525. Load Fluctuations.—Lighting systems have steady loads except for peaks. Industrial loads are very steady except certain kinds of applications to intermittent work using large units. Railway loads have considerable fluctuations.

(*a*) *The load factor of a machine, plant or system* is the ratio of the average power to the maximum power during a certain period of time. The average power is taken over a day or a year and the maximum is taken over a short interval of the maximum load within the period. The interval of maximum load should be definitely specified such as half-hour monthly load factor.

The annual load factor of a central station=

$$\frac{\text{Total kilowatt-hours generated per annum}}{\text{Kilowatts of maximum demand} \times 8{,}760} \times 100 \text{ per cent.}$$

$$= \frac{\text{Average load during the year}}{\text{Maximum load during the year}} \times 100 \text{ per cent.}$$

under the same conditions the average cost of generation and transmission per kilowatt-hour.

The same ratio taken for a day or other periods gives the *daily load factor*.

Example 10. A circuit carries a maximum load of 200 kW. and delivers an amount of energy equivalent to a load of 200 kW. during 3,000 hours per year ; determine the load factor for the year.

Solution.—

The load factor for the year$=3{,}000/24 \times 365 = 34{\cdot}2$ per cent.

(*b*) The *station load factor* on which the standing charge is based

$$= \frac{\text{Kilowatt-hours generated per day}}{\text{Kilowatts of plants installed} \times 24} \times 100 \text{ per cent.}$$

$$= \frac{\text{Average load}}{\text{Kilowatts installed}} \times 100 \text{ per cent.}$$

(*c*) *Plant load factor*

$$= \frac{\text{Average load}}{\text{Kilowatts of plants in use}} \times 100 \text{ per cent.}$$

The kilowatts are taken at rated full load. This is very nearly equal to the daily load factor.

(*d*) *The capacity factor* is the ratio of the average load to the total capacity of the equipment supplying the load.

The demand of an installation or system is the load which is drawn from the source of supply at the receiving terminals averaged over a suitable and specified interval of time.

(*e*) *The demand factor* is the ratio of the maximum power demand of any system to the total connected load of the system or of the part of the system under consideration.

(*f*) *Diversity Factor.*—In the distribution of electricity the maximum demands of consumers for general lighting and power purposes, are made at different hours of the day and vary from day to day during the week and from month to month during the year for various reasons. The demand for power purposes is greatest when the lighting load is smallest. The result is that the resultant maximum demand at the point of supply is less than what it would have been if these maximum demands were coincident. Thus the sum of the maximum demands of individual consumers is greater than that on the distributing mains, from which they are supplied. The sum of the maxima on distributing mains is greater than that of the feeder, the sum of the feeder maxima is greater than that of the sub-stations, and the sum of the sub-station maxima is greater than the coincident maximum of the generating station.

Diversity factor is the ratio of the sum of the maximum power demands of the subdivisions of any system or part of a system to the maximum demand of the whole system or of the part of the system under consideration, measured at the point of supply.

$$= \frac{\text{Sum of separate maximum demands}}{\text{Maximum demand on the station.}}$$

Example 11. The sum of the maxima of a group of feeders supplying a district is 5,000 kW. and the maximum demand upon the sub-station is 4,000 kW. Find the group diversity factor of these feeders.

Solution.—

5,000/4,000 = 1·25

526. Tariff :—(*i*) *Flat Rate.*—In this system a definite flat rate of so much per unit is charged to all consumers.

It is not satisfactory or fair, as the charge per unit is made high, and sometimes the profitable consumers subscribing at times of low-load have to pay the losses of the unprofitable consumers.

(*ii*) *Maximum Demand System.*—Electrical energy is generally sold by meter ; but this system of sale does not encourage the consumers who use energy at hours of small load or unusual hours. Hence, *the maximum demand system*, by which the consumer is charged *a certain sum per kilowatt of maximum demand*, and a low charge per unit actually supplied to cover the consumer's share of standing costs and to pay his share of the running costs, does not seem to be fair for all the consumers who have not loads of the same diversity factor.

The maximum demand system discriminates, to some extent, between *good and bad customers*, *i.e.*, one taking power at times of no-load and maximum demand, respectively, and is much fairer than the flat-rate system.

The object of maximum demand system is to (*1*) increase the profits of the undertaking, and (2) to diminish the price per unit paid by the consumer.

Maximum demand system may be subdivided into (*a*) that which makes a fixed charge per kW. of maximum demand, irrespective of the quantity of consumption in kW.-h. ; and of the purpose to which the current is supplied. This is applied in industrial loads supplied from hydro-electric system. This system is adopted at Simla. It avoids the use of meters in the case of very small consumers. (*b*) This involves great waste

for domestic supply ; a fixed charge is made per lamp of specified type and candle power. This makes a fixed annual charge per kW. of maximum demand *plus* a small additional charge per kW.-h , actually consumed, as shown by meter, regardless of the purpose to which the current is applied. This involves providing meters. Instances are found in Calcutta, Bombay and Madras where power is supplied for industrial purpose. This requires two meters, one to register the maximum amount of current in a given time and the other is an ordinary energy-meter which registers the total number of B. O. T. units consumed during the same period. The B. O. T. units registered on the energy meter are divided and charged for at two different rates,—the proportions of the total number to be charged at the high and low rates, respectively, depending on the reading on the maximum demand indicator.

Example 12. An installation is supplied on the maximum demand system at 8 as. and 2 as. At the end of a certain quarter the indicator registers a maximum demand of 3 kW., the reading of the energy-meter being 600 B. O. T. units. Find the charge for the quarter, the first 120 hours being taken at the maximum rate.

Solution.—

3 kW. × 120 = 360 units @ 8 as. = Rs. 180/-
600 — 360 = 240 units @ 2 as. = Rs. 30/-

Total Rs. 210/-

(*iii*) *The telephone system* is so called as it resembles the method of charging for telephone service. In this system also, there is a fixed annual payment based on certain percentage of the connected lighting load in advance and a small charge per unit actually utilised Convenient or decoration lighting and wattage installed, other than lighting, are not connected, and the consumer is, in any event, made to pay the standing charges on the fraction of the generating plant he requires to be placed at his disposal. It is better than maximum demand system, in which the customer pays nothing at all if he uses no current, although the generating plant has to be kept in

readiness to supply him ; while he pays less, for working at times of heavy load, than he ought to do. Note that the standing charges in a modern station are much higher than the running charges.

Example 13. Find the total charge per quarter for supply to the installation whose maximum demand is 100 kW. and in which the consumption per quarter is 50,000 kelvins. The fixed rate is Rs. 100 per annum per kilowatt demanded, and the price per kelvin is 2 annas.

Solution .—

The fixed charge per quarter $= 100 \times 100/4 =$ Rs. 2,500.
Cost of energy $= 50,000 \times 2/16 =$ Rs. 6,250.
Total cost = Rs. 8,750.

527. House Wiring :—It is often necessary to introduce the number of lamps and the percentage drop in volts ; it is also essential that local circumstances and each case should be considered separately, so that the lamps may receive the proper voltage and the leads may be designed so as to secure economy. If R is the resistance of the line, r is the resistance (hot) per lamp and n the number of lamps, then with a percentage drop, p, in the line we have—

$$\frac{p}{100-p} = R/(r/n) \text{ and } R = (r/n) \times \frac{p}{100-p},$$

but $R = \frac{10{\cdot}81 l'}{d^2}$, if l' = length of lead and return in feet

and

d = diameter in mils.

$$\therefore \; d^2 = \frac{10{\cdot}81\, l'\, n}{r} \times \frac{100-p}{p}$$

$$= \frac{21{\cdot}6\, Ln}{r} \times \frac{100-p}{p} \qquad \ldots \qquad (1)$$

where $L = \frac{1}{2} l'$ = distance of transmission in feet.

The product Ln is of the nature of a constant for a given installation, and is termed 'the lamp-feet' of the installation; r is also a constant for a given voltage lamp, and may be taken as $166\frac{2}{3}$ ohms for 100-volt lamps, 220 for 110-volt lamps, and $666\frac{2}{3}$ for 200-volt lamps. We may thus form a wiring table as follows. For 100-volt lamps and a 2 per cent. drop we have—

$$d^2 = \frac{21\cdot6}{166\frac{2}{3}} \times Ln \times \frac{100-2}{2}$$

$$= 6\cdot35\ Ln \quad \dots \quad \dots \quad \dots \quad (2)$$

Another very simple and useful rule, known as Sayer's wiring equation, may be used. If K=feet of cable per ohm resistance, then

since $e = IR$ and $R = l'/K$,

$$e = Il'/K \text{ and } K = Il'/e \quad \dots \quad (3)$$

and K is of the nature of a constant for each gauge of wire, therefore the wire to use is the one whose value of K is nearest to the value of Il'/e.

The side circuit for lighting should be arranged so as not to carry more than 5 amps. for circuits up to 125 volts, or more than 3 amps. up to 250 volts.

528. Maximum current carried by any insulated conductor, laid in the ordinary way, is given by—

$$\text{Log } I = 0\cdot82 \text{ Log } A + 0\cdot415$$

$$\text{or, } I = 2\cdot6\ A^{0\cdot82}.$$

where I is current in amperes, A sectional area in 1,000ths of a square inch.

In places where external temperature exceeds 100°F. (37·8°C.), the maximum current allowable will be less.

$$\text{Log } I = 0\cdot775 \text{ Log } A + 0\cdot301$$

$$\text{or, } I = 2\ A^{0\cdot775}.$$

In practice, however, the current in a given conductor is determined from a table as that of I.E.E.

Mr. Kennelly's formula for electric light cables for interior of buildings where the conductor is enclosed in wood casing:—

I=current in amperes which will raise the temperature of the conductor from 10°C to 24°C.

D= diameter of copper core of conductor.

$I = 560\ d^{\frac{3}{2}}$ ... d being in inches.

$I = 138\ d^{\frac{3}{2}}$ ... d being in centimetres.

529. Interior Wiring :—*The various systems of interior wiring* used in India are : (*a*) *the cleat system* :— It consists of rubber insulated and braided wire supported on porcelain insulator.

Advantage :—Very cheap and requires little skill

Disadvantages :—(1) Unsightly, (2) perishes quickly, (3) leaks and is only a make-shift.

(*b*) *The casing system* :—In this, rubber-insulated wires are run in suitable wood casing.

Advantages :—(1) Apparently simple.

Disadvantages :—(1) Majority of fires attributed to the fusing of an electrical wire and this is the most fruitful source of fires due to electrical causes, (2) generally unsightly on the surface, (3) the cost is much greater than cleat system.

(*c*) *Metal-sheathed system* :—In this, metal-sheathing is used to protect the insulating material of the wires from atmospheric conditions

Disadvantages :—The wires are expensive and somewhat difficult to instal owing to their stiffness and soldered joints are required at all joint boxes. Some other systems contain paper which absorb moisture readily, and great care is required to seal the ends of all the wires.

(*d*) *The twin wiring system* :—In this, two wires of a circuit are laid, side by side, after the insulation, which is of pure and vulcanised India rubber, and then sheathed with a special alloy containing a proportion of lead.

Disadvantages :—(1) It requires :—(*a*) proper bonding, and (*b*) earthing of the metallic sheathing ; (2) wants proper supervision ; (3) it contains rubber, which deteriorates in time, and is very badly damaged in moist places ; (4) it is very expensive ; (5) it requires skilled labour to locate faults.

In all the above systems, the wiring is replaced after a few years when the cost of the entire wiring is incurred afresh.

None of the above systems can be done outside the building or in moist places.

The metal-sheathed systems spoil the wall by having so many plugs in wall, and when leaks, it is dangerous.

(e) The author's "enamelled system of wiring" :—In this, bare copper wire is enamelled, or baked enamelled wire is carried on bobbin insulators, placed far apart, and the wires are separated from the walls. and, from each other, when necessary, by separating pieces to avoid the effect of electro-magnetic attraction or repulsion to produce the short circuit.

Advantages :—It is (1) by far the cheapest system ever invented; (2) absolutely permanent, having no rubber insulation to deteriorate in time, requiring no replacing after a few years; (3) having no inflammable rubber or varnished wood casing,—there is no chance of a fire; (4) it does not damage the walls by having too many plugs; (5) it has no leakage to occur, as it depends for insulation on suitable porcelain insulators; (6) it has no binding or earthing of the twin-wiring system; (7) it requires no skilled labour; (8) it can be used inside or outside a building equally well; (9) it is absolutely free from the attack of vermins; (10) it affords every facility for inspection to a lay man, as everything is open to inspection; (11) when painted and supported on decorative insulators, it may be made to match the colour of the wall, when it appears to be very decent.

The author's "improved system of wiring":—In this, enamelled or insulated conductors are taken through grooves in battens of wood properly impregnated with insulating compounds and supported on porcelain insulators. It may be placed flush with the wall.

Distribution Board System of House Wiring :— In this, the supply is led in through main fuses, and from these mains are run without reduction of size to distribution boards, which consist merely of a number of

fuses grouped together in a suitable casing ; and from these fuses smaller wires are taken to the switches and lamps, but no reduction is made in the size of wires after they leave the distribution boards The sub-circuits for lighting should be arranged so as not to carry more than 5 amperes for circuits up to 125 volts or more than 3 amperes up to 250 volts.

Exercises.

1. A dynamo is 100 yards from a house, the conductor has a resistance of 0·002 ohm per yard, and there are 150, 30-watt, 100-volt lamps to be fed. What E.M.F. must the dynamo give ? (C. & G.)

2. Two lamps of 100 and 150 ohms each, when running, are put in parallel with each other, and the pair is put in series with a lamp of 100 ohms. What E. M. F. will be needed on the system in order that it may consume 250 watts ? (C. & G.)

3. Thirty accumulators, each having an E. M. F. of 2·1 volts and a resistance of 0·002 ohm, are employed to feed incandescent lamps. If the lamps require 45 volts and 1·25 amperes each, what is the maximum number of lamps that can be employed ? (C. & G.)

4. Edison glow-lamps, requiring 108 volts potential difference and 0·72 ampere each, are required to be fed by accumulators, each having 2·1 volts E. M. F. and 0·0017 ohm resistance. What is the least number of such accumulators arranged in series that must be employed to feed 200 of these lamps in parallel ? (C. & G.)

5. In a water-power plant, the dynamo which produces a fixed P. D. between its terminals of 120 volts, is 300 yards away from the house. The usual load consists of 200, 100-volt, 55-watt glow-lamps. What size leads should be employed, if the resistance of a cubic inch of copper be 0·66 microhm ? (C. & G.)

6. A dynamo, maintaining a constant pressure of 220 volts between its terminals, supplies a power of 18,000 watts to a house 200 yards away. What must be

the cross-section of the copper of the leads so that no more than 4 per cent. of the power may be wasted in them ? Resistance of a cubic inch of copper may be taken as 0·66 microhm. (C. & G.)

7. A compound-wound dynamo, producing a terminal P. D. of 150 volts, is used to charge sixty storage cells, each having an E. M. F. of 2·2 volts and a resistance of 0·001 ohm. If the leads joining the dynamo and cells have a resistance of 0·2 ohm, what will be the current generated ? (C. & G.)

8. The declared pressure at which current is supplied to houses by mains coming from a central station is raised from 100 to 220 volts. If the percentage loss in the mains is to remain the same as before, by how much per cent. will their carrying capacity be increased when heating limit has not to be regarded ? (C. & G.)

9. A dynamo, driven with water-power at a constant speed, supplies energy to 50, 60-watt lamps and a 20 B. H. P. motor, used for driving a saw-mill 1,000 yards away ; consider what kind of dynamo and motor you could use, and what electric pressure would be suitable. Calculate approximately the cross-section you would give to the mains, the drop in pressure that would occur, and the power required to drive the dynamo at full load. (C. & G.)

10. A building of four floors has ninety 8-candle-power lamps on each floor ; the height of each floor is 18 feet, and the mains run straight up in the middle of the building. On each floor is a passage extending 100 feet each way from the middle, and in the passage, on each side of the middle, are five lamps. Opening out of the passage, on each side floor, there are twenty rooms containing two lamps. Calculate the size of the mains going from the bottom to the top of the building, of the submains in the passages, and of the lamp leads, on the supposition that when all the lamps are turned on, the drop in pressure from the basement to the farthest lamp does not exceed 2 volts, and that the pressure supplied is 100 volts. (C. & G.)

11. A four-storied mill is to be lighted with 200, 16-candle-power, 200-volt lamps on each floor, and the height of the mill is 48 feet. Design a system of mains from the switchboards on the respective floors to the main switchboard, which is 80 yards distant from the point where the mains enter the building—such that each floor shall be independent of all the others, and the drop of pressure between any switchboard and the main switchboard shall not exceed $1\frac{1}{2}$ per cent., when all the lamps in the building are turned on. (C. & G.)

12. A pair of feeders, each half a mile long, have to deliver 100 kilowatts at 440 volts. What cross-section must they have so that the loss in them may not exceed 5 per cent. of the power delivered ? (1 inch cube of copper has a resistance of 2/3rd microhm). (C. & G.)

13. A, B, and C are three points, each at a distance of 157 yards from the next. At A there is a dynamo ; at B a group of 200 incandescent lamps, requiring 110 volts and 0·75 ampere each ; and at C a group of 250 lamps requiring 100 volts and 0·83 ampere each. Calculate the diameter of the copper conductor that must be used for the lead and return wires between A and B, and between B and C, respectively, if the potential difference maintained at the terminals of the dynamo is 112 volts. 1 yard of commercial copper wire, 1 square inch in section, has 0·00002435 ohm resistance. (C. & G.)

14. Current is required along a street 2,000 feet long, at the rate of half an ampere per foot run, or in all, 1,000 amperes. The voltage drop between any two points of the mains must not exceed 4 volts. The generating station is at one end of the street. State the size of the main and total weight of copper for the two following cases :—(*a*) The station is directly connected to the end of the main ; (*b*) the station is connected to the middle of main by a feeder of such size that 10 volts are lost in the feeder. Include the weight of the feeder in giving the total copper weight. *N. B.*—A bar of copper, 1 square inch in section and 1 mile long, has a resistance of 0·0425 ohm. 1 cubic inch of copper weighs 32 pounds (C. & G.)

15 You have, in a street, a pair of mains, each conductor 0·2 square inch in area (0·12 ohm per 1,000

yards), and the demand for current is at the rate of one 30-watt 100-volt lamp per yard run. Give distance between the feeding-points, so that the maximum variations of pressure between any two consumers shall not exceed 3 volts. (C. & G.)

16. You have to deliver 115 electrical horse-power, by means of a continuous current, $1\frac{1}{2}$ miles distant from the generator. The terminal pressure at the generator is 1,000 volts, and the loss due to line resistance is assumed to be $7\frac{1}{2}$ per cent. of the power delivered. Give the size and weight of the conductor required. *N. B.*—A bar of copper, 1 square inch in section and 1 mile long, has a resistance of 0·0425 ohm. The specific weight of copper is 8·9. The insulation of the line is perfect. (C. & G.)

17. A room containing 60 lamps is at a distance of 200 yds. from the dynamo: what must be the diameter of the copper-main leads so that the potential difference at the lamps is not less than the potential difference at the terminals of the dynamo by more than 1 per cent. (*a*) when the lamps require 45 volts; (*b*) when they require 110 volts? 1 yard of commercial copper wire, 1 square inch in each section, has 0·00002435 ohm resistance. (C. & G.)

18. The pressure at which a certain amount of power is delivered to a line is doubled. Determine (*a*) the effect on the power wasted, (*b*) how much the area of cross-section may be diminished so that the losses may be the same as before, and (*c*) how much the original line may be lengthened so that the losses may be the same as before.

19. The electric lighting of a block of buildings is effected from an engine-room 1,350 yards distant. The wiring of the block is arranged for the three-wire system, and is fed by a three-wire feeder, the cross-sectional areas of the conductor cores of which are 0·5, 0·25, 0·5 square inches, respectively. There are 700 lamps of 16-c. p. in use of the circuits connected with one side of the three-wire system and 550 on the other. What voltages must be maintained at the generating station ends of the

feeder between the positive and negative conductors and the neutral, respectively, in order that the pressure between the terminals of each of the distributing circuits may be 205 volts ? The current required by a 16-c.p. lamp may be taken as 0·3 ampere, and the resistance of a cubic inch of copper 0·66 microhm. (C. & G.)

20. Determine the most economical current-density of a feeder which has to be used twelve hours per day, if the cost per B. T. U. is 0·8d., price of copper per ton £200, and interest be charged at 9 per cent.

21. In a certain transmission plant 400,000 watts of electrical energy at 1,000 volts are delivered at a point 440 yards from the generating station. If the conditions are the same as in No. 16, determine (*a*) the most economical cross-sectional area of the feeder ; (*b*) the drop in volts per mile ; and (*c*) the E. M. F. at the generating station.

22. Illustrate Lord Kelvin's law of economic proportion in cost of lines by an example of continuous-current power transmission, taking the case of a line for delivering 100 H. P. at a distance of 4 miles, maximum voltage 3,000 volts. (C. & G.)

Give the cross-sectional area if cost of B. T. U. is 0·75 d. price of copper £ 200 per ton, interest 10 per cent , and that the power is required twelve hours per day.

CHAPTER X

PROTECTIVE APPLIANCES

530. Conditions against which protection is required :—The systems and devices used to protect electrical circuits in general have the following two main functions to perform :—(1) The prevention of damage in all possible cases, and its restriction in others, as far as its degree and extent are concerned. (2) The maintenance of supply and operation in all parts, excepting the portion affected.

531. Damage to circuits or apparatus may be effected by the following principal causes, and protection is, therefore, required against these :—(*a*) Excessive current caused by overload or short circuits. (*b*) Excessive pressure caused by switching surges, resonance or lightning. If an inductive load is suddenly broken, there may be considerable rise of pressure which may damage the apparatus, *e.g.*, when the field circuit of a motor is broken. In such cases a non-inductive resistance should be put as a shunt at the instant of pressure. To prevent pressure rise due to arcing and sparking, avoid all chattering contacts and use good switches to close the circuit clearly. (*c*) Failure of insulation, resulting in leakage to earth or between wires. (*d*) Low voltage, or complete failure of supply due to loss of voltage at the generator, transformer, etc., feeding the circuit, or interruption in the circuit. (*e*) Reversal of current or power flow. (*f*) Fire risk. The necessity of protection has risen with the voltages and powers concerned in electricity supply systems, and though the initial cost of protective set may be high, it is economical in the long run, *viz.*, when compared with the value of the equipment protected, or with the cost of the damage which might otherwise occur. Protection is mainly required against *sustained overload, high temperatures* and *internal faults.*

The protective system should be satisfactory from the following points : (1) *Selectivity*. The protective system should be able to distinguish which portion of a sectionalised system is in trouble and to disconnect it, only leaving the remaining part free to function normally. (2) *Perception*. It should distinguish between normal and abnormal conditions with a high degree of accuracy. (3) *Sensibility*. It should not allow unduly large growth of the fault before the protective actions are completed.

PROTECTIVE APPARATUS

532. Automatic Protection :—It falls into two classes :—(1) Protection by circuit breaking equipment against overload, short-circuit and other dangerous conditions of the circuit.

(2) Protection by lightning arrester equipment against sudden and excessively high voltages, due to lightning and other line disturbances.

533. Circuit Breaking Equipment :—

(*a*) *Fuses*.—These are commonly used on low voltage, such as lighting circuits, and the primaries of transformers than on high voltage, and for small than for large currents ; and are suitable in cases where a relatively small inexpensive piece of apparatus is required, which does not operate often, but which offers positive protection against a short circuit. These are the simplest means of automatically opening a circuit under short circuit or overload condition. But under normal conditions the fuse may fail to carry its rated load because of insufficient opportunity for radiation, or because of insufficient contact surface at its terminals, which may add to the heat instead of assisting in carrying it away.

534. Installation of Fuses

1. Covered fuses are more sensitive than open ones.

2. Round fuse wire would not be employed in excess of 30 amperes' capacity. For higher currents flat ribbons, exceeding four inches in length, should be employed.

3. On small circuit upto 40 amperes tin and lead fuses are suitable.

4. Lead and tin fuses have low melting points, but they are easily damaged, and their cross-section is altered,—so do not tighten up the binding screws too much. The use of the hard metal tip is to afford a strong mechanical bearing for the screws, or other devices provided for holding the fuse. Copper fuse (1) is not so easily scratched or squeezed, (2) throws about less metal when the fuse blows and is far more reliable than tin or lead.

5. Enclosed fuses of standard sizes are preferable to link fuses. Where the link fuses are used, they should have contact surfaces of harder metal, having perfect electrical connection with the fusible part of the strip.

6. They should be stamped with about 80 per cent. of the maximum current they can carry indefinitely, thus allowing about 25 per cent. overload before the fuse melts.

LENGTH OF FUSE

Current.	Up to 300 volts.	Up to 600 volts.
Up to 10 Amps.	1·5 inches.	4·5 inches.
,, 15 ,,	2·0 ,,	
,, 20 ,,	2·5 ,,	
,, 40 to 100 ,,	3·2 ,,	6 inches.
,, 100 to 200 ,,	4·5 ,,	

7. (*a*) The lengths of fuses and distances between terminals are important points to be considered in the

proper installation of these electrical "safety valves." No fuse block should have its terminal screws nearer together than one inch on 50 or 100-volt circuit and one inch additional space should always be allowed between terminals for every 100 volts in excess of this allowance.

Example 1. If a motor protected by two sets of fuses is 20 H. P. on a 220-volt line, having 80 % P. F. and 80 % efficiency at rated loads, what size fuse should be used ?

Solution.—

$$\text{Rated current} = \frac{20 \times 746}{\sqrt{3} \times 220 \times 0{\cdot}75 \times 0{\cdot}80}$$

$$= 65{\cdot}34$$

The running fuse capacity should be $65{\cdot}34 \times 125\ \%$ $= 81{\cdot}68$ amperes. The nearest standard size is 85 amperes. The capacity required in starting fuses depends on the rate of acceleration of the motor ; the slower it is in coming to speed, the larger must be the fuses. Assuming a starting current of three times the normal, the starting fuses should be between 200 and 250 amperes.

535. Circuit Breakers :—These are to be used on all circuits larger than 400 to 600 amperes and even on short circuits, where overloads or short circuits are likely to be frequent, or high voltage and large current. The rated ampere capacity of circuit breakers should be based on the maximum current that the lines are expected to carry.

The ultimate breaking capacity is the largest current that the breaker is expected to open. It is used in D. C. generator and feeder circuits and in A. C. feeder circuits, but not in A. C. generator circuit.

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536 Oil Circuit Breakers :—The accumulation as well as the distribution of great amounts of power are made through oil circuit breakers. This is an important

and quite an expensive apparatus. Its application depends upon any number of the following requirements :— such as : voltage, normal current capacity, short line current capacity, interrupting capacity, safety features, methods of operation, adaptability to a particular arrangement and other requirements for the particular case under investigation.

The inter-connection of systems of power transmission has necessitated greater care in the selection of oil circuit breakers where the circuit is to be interrupted under short circuit conditions. The amount of power to be interrupted under these conditions may be one of the most important features in determining the type of capacity of breaker to use.

Principal of O. C. B. :—The main advantage that the oil circuit breaker possesses is that the circuit is broken near to the zero point on the current wire ; when the switch is opening, the arc goes out as the current falls to zero and the voltage has to rise to a certain value before the oil between the contacts is punctured. This arc is maintained until the current falls to zero again, when the process is repeated until there is no longer sufficient energy to restrike the arc. The circuit is then to be completely interrupted.

Operation :—Small size oil circuit breakers are usually operated normally by means of a lever mounted on the breaker itself. This method is impracticable to operate layer breakers, because the operator will have to use lot of mechanical strength to close the contacts properly. Under such cases, the oil circuit breakers are electrically operated.

The two methods of electrical operation, considered as the standard ones, are (1) solenoid, (2) motor operations. Standard solenoid operation renders itself possible, only, if direct current supply is available, whereas the motor operation can be done with either supply. The solenoid method of operation permits mounting the operating mechanisms on the cell walls or on pipe frames or on the breaker. The operation of the solenoid is

done at a remote control point by a push-button switch. On account of the large amount of current taken by the closing-coil, the control-switch operates a control-relay, which, in turn, closes the main solenoid circuit. The control-relay is described later.

Breakers are motor-operated only when the particular design of breaker lends itself to be economically operated by it. Usually high operating speeds are obtained by the use of motor mechanisms, owing to the immediate available energy stored in the operating springs, than are obtained by the use of solenoid mechanisms, since time is required for the building up of the magnetic field after the control circuit is closed. Usually the transformer bank switches and line switches are motor-operated.

The solenoid-operating mechanisms are coupled to the breakers by means of an operating pipe, so that all three poles of a unit are operated simultaneously in the opening and closing direction. Auxiliary switches for lamp indications (red lamp when the circuit is on, green lamp when the circuit is off) are included. The torque exerted by mechanisms is such as to assume rapid and correct travel to obtain proper successful functioning of all interrelated parts and mechanisms.

Both operating devices of oil circuit breakers contain provision for emergency manual operation by means of an emergency lever Auxiliary switches are mechanically connected to the link system of the mechanism.

537. Selection and Application of Oil Circuit Breakers:—(1) Normal pressure in volts of the circuit to which the oil circuit breaker is to be connected. In systems employing transformers, the normal voltage of the system is to be considered as the highest rated voltage of the secondaries of transformers supplying the system.

(2) The normal R. M. S. current of the circuit to which the breaker is to be connected.

(3) The length of time of short circuit and magnitude of current rushing under short circuit conditions that the breaker will be subjected to.

***540. Consideratoins which determine the size of the Circuit Breaker :—**

1. The best engineering practice is to put circuit breakers in D. C generator and feeder circuits, and in A. C. feeder circuits, but not in A. C. generator circuits.

2. A D. C. generator may deliver on short circuit, for an instant, about 30 times full-load current, but the heavy current rapidly demagnetises the field, reducing the voltage and the short-circuit current, so that after 2 secs. the breaker need only be one that will open 10 times full-load current at rated voltage.

D. C. Generator Circuit :—If the breaker is set for instantaneous operation, it should have an ultimate capacity of 30 times full load. If the operation of the breaker is delayed for 2 secs., the ultimate capacity need be only 10 times the full load.

D C. Feeder Circuit :—Breaker's ultimate capacity should be 10 to 30 times the sum of the full-load currents of all the generators.

For example, if four D C generators are in operation at one time, and each generator capacity is 100 amps., the ultimate breaking capacity of each feeder breaker should be 4,000 to 12,000 amps., even though it may carry normally, say, 100 amps.

3. An A. C. generator will deliver on short circuit, for an instant, usually, 12 times full-load current; but the heavy current demagnetises the field, reducing the voltage and the short-circuit current, so that after 2 secs., the breaker need only be one that will open 10 times full-load current.

4. If several A. C. generators are connected in parallel to the same buses, the short-circuit current in a feeder is the sum of the short-circuit currents of all the generators, because the A. C. generators themselves have individually no overload protection.

5. If the circuit breaker is in the secondary circuit of a transformer, or at a distance out on a line, the short-circuit current is reduced by the transformer line

* Brown's Electrical Equipment.

impedance. If the transformer capacity is small, compared with that of the generator, the short-circuit current depends chiefly on the transformer rather than on the generator. Ordinary transformers, with high-tension windings of 16,500 volts or less, have an impedance drop of 2·5 to 4 per cent. at full load, so that the short-circuit current (*i.e.*, at 100 per cent. drop) is from 40 to 25 times full-load current.

A. C. feeder circuit breaker is in the secondary circuit of a transformer, the ultimate breaking capacity need not exceed 25 to 40 times the transformer-rated capacity. (Information can be obtained from the manufacturer as to the short-circuit current on any transformer).

If the breaker is at a distance from the generator, the ultimate breaking capacity need not exceed the short-circuit current on the line, which is the rated line voltage divided by the line impedance.

Example 2. Determine the ultimate capacity of a circuit breaker which is to be used on a 2,200-volt, 50-cycle circuit, 500 ft. long, consisting of 19/0·092 conductors, spaced 2′-6″ apart.

Solution.—

Line impedance for two wires $= 0·629 \times 500/5{,}280 = 0·595$ ohm.

Short-circuit current 2,200/0·119=3,697 amps., which is the required ultimate capacity of the breaker.

If the breaker is near the generator and is not in the secondary circuit of a transformer and opens instantaneously, its ultimate breaking capacity should be about 12 times the rating of the generator. If there are two or more generators, it should be 12 times the sum of the rated capacities. If the breaker does not open for 2 secs., its ultimate capacity need be only 2 or 3 times the sum of the generator capacities, and if more than 2 secs., the capacity is still more reduced.

Example 3. If there are three 500-K. V. A., 2,200-volt, three-phase alternators in a station and the

circuit breakers are set for a 2-sec. limit, determine the ultimate capacity of the circuit breaker.

Solution.—

The ultimate breaking capacity of the circuit breakers should be $3 \times 3 \times 500 \times 1{,}000/(2{,}200 \times 1 \cdot 73)$, or 1,183 amps.

541. Care and Maintenance of the Oil-Immersed Circuit Breakers :—

General :—Regularly the inspection should include cleaning, lubricating, operating and tripping the breaker several times by each means provided. A more thorough inspection and overhaul with the tank lowered should be carried out, as soon as possible, after the breaker has opened under heavy current or short-circuit conditions. Even if the breaker is not suspected of having operated on abnormal conditions, thorough inspection should be carried out in any case at *intervals of 6 to 12 months.*

Cleaning :—All parts should be kept clean and the porcelain insulators should be wiped down with clean cloth (not cotton waste).

Operating Mechanism :—The breaker should be closed and opened several times during which every method of closing should be tested (not forgetting the emergency handle for electrically-operated breakers). When opening, each method of tripping should be tested, *i.e.*, the breaker should be tripped by hand, by each automatic release in turn, by every protective relay, by push-button, and by interlocking gear, if provided. If a tripping battery is used, it should be arranged to trip the breaker.

The bearing and moving parts of the operating mechanism should be lubricated, where necessary, and surplus oil wiped off.

Contacts :—For special inspection, overhaul, and always after the breaker has operated under short-circuit conditions, the tanks should be lowered and the fixed and moving contacts examined, pitting being removed where necessary. The breaker should be

closed with the tank off, to make sure that the contacts close properly and that the contact pressure is sufficient.

Oil :—The oil level should be examined every 6 months, or more frequently, if signs of the oil are observed below the breaker. Large-size breakers have oil indicators and the medium size have a plug dipped in the filling hole in the switch top. To check the oil level, this plug should be removed. If the button of the plug dipper is dry, the oil should be replenished. On small-size breakers it is necessary to remove the tank and check the oil level, which should be maintained at the marked level.

Whenever oil tank is lowered, oil should be examined, and if it is badly discoloured, it is advisable to change it, or re-condition it immediately. The intervals at which the oil should be replaced depend on the conditions of working and for the sub-station breakers, operating unfrequently in a clean and a well-ventilated station, the oil should be good for two or three years. For heavy-current circuit breakers and for circuit breakers operating frequently on the D. C. system, it is advisable to replace or re-condition the oil every 6 months.

Final Inspection :—Before putting the O. C. B. into commission, a final check should be made upon the complete apparatus to ensure that everything is in working order. For instance, all the mechanical joints should be perfectly tight and in attending to this, care should be taken that the bolts are tightened in rotation, so as to ensure uniform pressure. None of the tools used is left inside the apparatus to prevent serious accidents.

542. Auxiliary Switches :—Auxiliary switches may be for circuit closing and circuit opening, or combined circuit closing and opening.

The circuit-opening switch opens an auxiliary circuit when the breaker opens. It is also used in some cases with a shunt trip-coil attachment to immediately disconnect the shunt coil from the circuit. It is also used to

indicate, by a lamp on an alarm signal, the closed position of the breaker, to trip another breaker having an under-voltage release, and to allow another breaker to remain closed only when the breaker is equipped with the auxiliary switch.

The circuit-closing switch closes an auxiliary circuit when the breaker opens. In case the opening of one breaker is required to another device, or if it is desired to electrically interlock the breaker with the other devices, the circuit-closing switch is used with an under-voltage release or shunt trip attachment on the devices to be opened. This switch is also used for the purpose of indicating, by a lamp or an alarm signal, the opening position of the breaker. The combined circuit closing and opening switch performs all the functions of the two separate switches.

543. Control Relay :—Control relays are used to energise the closing coil of the solenoid, to take the heavy load and an inductive arc of the closing coil off the control switch, which, therefore, has to open the current of the control relay coil. When two or more solenoid-operated circuit breakers are operated by one control switch, one control relay is also used to energise the trip coil. The control relay, being located in the immediate vicinity of the circuit breaker, is usually upon the supporting framework.

544 Application of Disconnecting Switches :—Fig. 10'02 shows the application of the connecting switches 1 and 3, or 2 and 4, for disconnecting transformers for sectionalising buses 6 and 8, or 7 and 9, for disconnecting a circuit breaker 10 or 11 for disconnecting a lightning arrester, if necessary.

545. The Difference between D. C. and A. C. Generators on Short Circuit :—Short circuit of D. C. generators is a very serious matter. The commutator usually flashes over, and the belts and shaft are put to a dangerous strain. The short circuit of alternators results in no excessive stresses. It involves the passage from one steady state of normal operation to another steady state

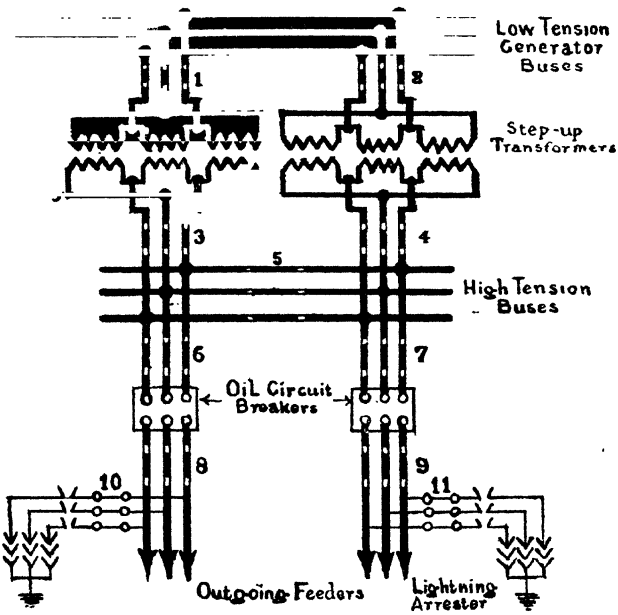


Fig. 10'02.

of permanent short-circuited condition which succeeds the transient period ; the machine is thrown out of equilibrium, and difficulties occur in the transient period.

546. Short-Circuiting of an Alternator :—

Let e_1 = the initial value of E. M. F.,

e_f = final value of the E. M. F.,

e = the value during the transient period,

θ = the phase angle,

θ_1 = the phase angle at the instant when the short circuit occurs.

Then $e = E_m \sin \omega t$

$e_1 = E_{fm} \sin \omega t$ final value.

$$e = E_m e^{-\frac{r_0}{L_0}(t - t_1)} \sin \omega t + E_m \sin \omega t$$

i.e., it is the sum of the final value and a transient term, the latter being proportional to the instantaneous value of the flux. In terms of phase angle—

$$e = E_m e^{-\frac{r_0}{x_0}(\theta - \theta_1)} \sin \theta + E_{fm} \sin \theta \qquad \ldots \quad (1)$$

$\theta - \theta_1$ represents any time elapsing after the instant of short circuit.

(*a*) The condition for maximum current is when $\theta_1 = 0$ and $\theta = \pi$.

$$\text{Then } i = \frac{E_m}{x} \left[e^{-\frac{r}{x}\pi} + e^{-\frac{r_0}{x_0}\pi} \right]$$

The value of r_0/x_0 is about 0·02 in all alternators and $(r_0/x_0)\,\pi = 0·06$ giving $e^{0·06} = 1$, approximately. Therefore, the maximum current at short circuit is

$$i = (E_m/x) \left[e^{-\frac{r}{x}\pi} + 1 \right]$$

Evaluating, $(r/x)\,\pi$ is from 0·6 to 0·8.

$\therefore\ i_{max.} = (E_m/x) \times 1·75$, approximately.

Example 4. An alternator has 5 per cent. reactance. Find the greatest possible current that can be obtained on short circuit.

Solution.—

$i_{max.} = (1/0·05) \times 1·75 = 35$ times the normal current.

(*b*) Before the alternator is short-circuited the stored electromagnetic energy is $\frac{1}{2} L i^2$, where L is the inductance of the field system and i the field current.

Now $L = n\,\phi/i\ 10^8$.

The energy is $w = \frac{1}{2} n\,\phi\ i/10^8$ joules.

Since it has been assumed that the flux at any instant is determined by the equation—

$$\phi = \theta e^{-\frac{r_0}{x_0}(\theta - \theta_1)}$$

the energy given out in any period of time is

$$w = \tfrac{1}{2}(\phi_0 - \phi_1) ni/10^8,$$

which may be determined from the known constants.

Example 5. In a four pole machine $\phi = 200 \times 10^6$ lines of flux per pole,

$n = 400$ turns per pole,
$i = 100$ amperes field current.

Determine the energy given out by the disappearance of the flux.

Solution.—

$$L = \frac{400 \times 200 \times 10^6}{100 \times 10^8} = 8 \text{ henrys per pole.}$$

If all the flux is destroyed, the energy is

$$w = 4 \times \tfrac{1}{2} L i^2 = 4 \times 0.5 \times 8 \times 10{,}000$$
$$= 160\,000 \text{ joules}$$
$$\text{or, } 160 \text{ kW. second.}$$

If this energy disappears in 1/25 sec., the average power during this short interval is $160 \times 25 = 4{,}000$ kW., which is furnished by the destruction of the flux

*** 547. Stresses on End Connections of Armature Coils :—**

Consider two similar conductors of radius r, placed at distance d between centres.

To find the average flux through conductor B due to the current in the conductor A.

The flux through any element dx, of B per centimeter length of the conductor, is

$$d\phi = \frac{4\pi I \mu dx}{2\pi x} = \frac{2 I dx}{x}.$$

* Berg and Upson's Electrical Engineering.

where I is in absolute-amperes, and μ is taken as unity. The average flux density is then

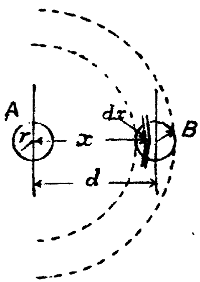


Fig. 10'03.

$$\phi_{av} = B = I/2r \int_{d-r}^{d+r} 2I\,dx/x$$

$$= (I/r) \log \frac{d+r}{d-r}.$$

Generally, the force exerted is $B\,I\,l$ dynes, where l is the length of the wires in centimetres.

Thus force per cm. $= \frac{F}{l} = \frac{I^2}{r} \log \frac{d+r}{d-r}$ dynes.

If I is in ampere, $\frac{F}{l} = \frac{I^2}{100r} \log \frac{d+r}{d-r}$.

If dimensions are given in inches, the formula remains the same.

Example 6. Two adjacent conductors, each of area 0'126 sq. in., are placed side by side. The current density is 2,000 amps per sq. in. under normal conditions. Find the maximum normal current and the maximum force under normal load.

$$d = 0{\cdot}5,\ r = 0{\cdot}2,\ l = 20.$$

Solution.—

$I = \sqrt{2} \times 0{\cdot}126 \times 2{,}000 = 361$ amps.

The maximum force under normal load,

$$F = \frac{(361)^2 \times 20}{100 \times 0{\cdot}2} \log \frac{0{\cdot}7}{0{\cdot}3} \text{ dynes.}$$

Temperature rise on short circuit:—It may be found from the formula $\frac{0{\cdot}012 I^2}{A_2 \times 10^6}$ °C. per sec., where A is the cross-section in square inches.

548 Multiphase Short Circuit:—

$$e_x^* = E \sin(\theta + 120)\, e^{-\frac{r_0}{x_0}(\theta - \theta_1)}$$

$$i_m = \frac{E}{x}\left[e^{-\frac{r}{x}(\theta-\theta_1)} \cos(\theta_1 + 2\pi\, m/n) - e^{-\frac{r_0}{x_0}(\theta-\theta_1)} \cos(\theta + 2\pi\, m/n)\right]$$

where n is the number of phases and m has the values 0, 1, 2, 3, ...$(n-1)$.

From the above equation the short-circuit current can be deduced.

549. Bus-Stresses:—In the larger generating stations, due to the tremendous values of short-circuit currents, resulting from the size and number of generators represented in present-day station practice, close attention must be given to the adequacy of bus-bar supports. Various curves and formulæ have been deduced for the purpose of calculating the mechanical strain on bus-bar supports at the instant of short circuits. A typical formula is the following—

$F = 0{\cdot}27 \times$ K. V. A.^{2}, divided by $A \times V^2 \times Z^2$,

where F = maximum force exerted in pounds per foot of bus-bar,

K. V. A. = normal rating of the station including a synchronous apparatus,

A = distance between buses in inches,

V = line voltage,

Z = impedance in per cent. expressed in decimals to the point of short circuit.

In using this formula a typical example with 150,000-K V. A. station capacity at 6,600 volts, 8 per cent. reactance, gives a maximum force on bus-bars per foot of length, 735 pounds with 30″ spacing between bars, 1,470 pounds with 14″ spacing between bars.

Note.—Laminated bus is an advantage, as it gives more radiating surface, better connections and the capacity can be increased by adding more laminations.

550 Bus Size:—The basis is a current density of 800 to 1,000 amperes per square inch. The temperature, however, is the controlling factor. The minimum temperature rise of 30° C. above the room temperature, with a maximum temperature of 70°C., is the limitation on which the design is to be based. Besides this, the consideration of mechanical rigidity determines the size of bus-bars and the distance between supports. Many factors enter into the heating of a bus. such as, variation in radiation, air convection, skin effect, reactance due to bus arrangement and eddy currents.

$\frac{1}{8}$ and $\frac{1}{4}$ inch thicknesses are most commonly used. If two or more sections are used, the spacing between them is generally $\frac{1}{4}$ of an inch apart.

Bus spacing:—Taking the permeability in air$=1$

$F = 2\, I^2\, L/d$ in C. G. S. units,

$$= \frac{54\, I^2}{10^8\, d} \text{ lbs. per ft. of bus}$$

for a D. C. bus and also gives average force on a single phase A. C. bus.

The maximum value of asymmetrical current waves (as are sometimes produced by short circuit) may be twice that of symmetrical form.

Thus $I^2_{max.} = (2\sqrt{2}\ I)^2 = 8I^2$

Thus the equation for a single-phase A. C. short circuit is $F = \dfrac{432 I^2}{10^8 d}$ ... (1)

For three-phase bus, phases being in one plane,

$$F = \frac{324 I^2}{10^8 d} \quad \ldots \quad (2)$$

For equilateral spacing of a three-phase bus,

$$F = \frac{374 I^2}{10^8 d} \quad \ldots \quad (3)$$

In practice, F is increased to stand the impact due to the sudden application of the short-circuit forces. The bus-bar supports must be so arranged and spaced that the safe compression, tension, or transverse force upon the insulator is not exceeded. Manufacturers of insulators usually state in their catalogue the allowable insulator loads. The bus must act as a continuous beam from insulator to insulator, stressed within the elastic limit. The moment due to uniform loading imposed by the force of W lb. per ft. is to WL^2 inch lbs. (L being in feet).

$$\text{Now } M = PS \qquad L = \sqrt{\frac{PS}{W}}$$

Where L=distance between supports in feet,

P=working stress of bus metal 8,500 lbs. per sq. in. for copper.

S=section modulus of bus cross-section inches^3.

For rectangular bus it is bd^2 ; for circular tubes

$$\frac{\pi}{32d_1}(d_1^4 - d_2^4)$$

W=force F *plus* allowance for impact due to the nearly instantaneous nature of the application of F during a short circuit. It is well to allow 100 % for impact, and sometimes for dead weight of the bus or attached equipment, or for the pull that will be exerted on it due to the manual opening of the bus-disconnecting switches. Provide, in long bus-bars, some means of meeting thermal expansion and contraction. Long buses are often divided into short sections which are joined by flexible copper straps.

Example 7. A 60-cycle, 3-phase bus will transmit a maximum of 20,000 K. V. A. at 6,600 volts. Design the bus-section based on 30°C. rise over 40°C.

Solution.—

$$\text{Phase current} = \frac{20{,}000 \times 1{,}000}{6{,}600\sqrt{3}} = 1{,}750 \text{ amps.}$$

Assuming the current-density of 800 amps./sq. in., the required area $= \dfrac{1,750}{800} = 2{\cdot}2$ sq. ins.

If this were in laminations $\frac{1}{4} \times 4''$, the required number of laminations would be $\dfrac{2{\cdot}2}{4 \times \frac{1}{4}} = 2{\cdot}2$, say, 3.

Bus ratings :—Amperes per sq. in., based on 30°C. rise over 40°C. temperature. We find for 4″ width, 2 laminations, assuming the current density to be 1,050 amps per square inch.

Required area of bus = 1,750/1,050 = 1 66 sq. in. 2 laminations $4'' \times \frac{1}{4}''$ give 2 sq. in. area.

Example 8. Suppose the phases are in line, and separated on average of 12″. Assume, that the short-circuit calculations have shown that the R.M.S. value of a single-phase short circuit will be 8 times the normal current. The insulator manufacturer states that the maximum transverse-load should not exceed 800 lbs. per insulator. The insulator spacing should be found first on the basis of insulator strength, second on the basis of bus-bar strength.

Solution.—

Normal current=1,750 amps.

Short-circuit current $= 8 \times 1,750 = 14,000$ amps. Single-phase short-circuit current on adjacent phases produces the maximum force. Here $d = 12$ ins.

Substituting in equation (1) above,

$$F = \frac{432 \times 14,000^2}{10^8 \times 12} = 70{\cdot}56 \text{ lbs. per ft.}$$

Including 100 % impact

$$F = 2 \times 70{\cdot}56 = 141{\cdot}12 \text{ lbs./ft.}$$

Insulator spacing $= \dfrac{800 \times 12}{141{\cdot}12} = 68$ inches; considering each lamination to act as a separate continuous beam of 4″ breadth and $\frac{1}{4}$ in. depth, carrying $70{\cdot}56/2 = 35{\cdot}28$ lbs. per ft.

$S = \frac{4 \times (\frac{1}{4})^2}{6} = \frac{1}{24}$, and substituting in the equation.

$$L = \sqrt{8{,}500 \times \frac{1}{24} \times \frac{1}{35{\cdot}28}} = 3{\cdot}16 \text{ ft.}$$

Insulator spacing $= L \times 12 = 3{\cdot}16 \times 12 = 37{\cdot}92$ inches. This is the governing dimension, if the bars are placed vertical. If they are laid flatwise, the ventilation would not be as effective but the strength would be so much greater that the insulator strength would be the governing dimension The size of the bus copper was calculated on the basis of the most effective ventilation.

551. Bus Protection :—Automatic bus sectionalising is important, on rare occasions, to localise the fault by means of current transformers in the bus-actuating relays that control the circuit breaker. Sometimes this is done to change a complicated system to a simple one at the time of fault. It may also reduce the duty on main O. C. B. by cutting off the current from neighbouring bus-sections. To do this, the sectionalising relay must actuate its breaker instantaneously or at least ahead of the main breaker. Over-current relays can be used more easily for sectionalising into two sections than for more than two; because, where there are several sections, there is danger of isolating one bus-bar section due to its carrying current of another bus section.

Where bus-sectionalising, by means of over-current relays, is impracticable, on account of any doubtful or impossible selective action, differential protection can be used.

Advantages of Bus Protection :—

(1) Restricts a fault to one section of the bus.

(2) Simplifies the system in times of trouble by eliminating interconnections.

(3) Reduces duty on main circuit breaker.

(4) Protects other bus sections and its feeders.

Disadvantages :—

(1) Additional cost of equipment.
(2) Possibility of isolating a good section.
(3) Possibility of operation on through shorts.
(4) Not readily applicable where the bus is divided into several sections.

552 Switchgear.—The increasing use of electrical energy and its economical production require the use of larger generating stations and linking together of the existing plants. In order to tie the generating stations together, and also to transmit power to a longer distance, the engineering problem is towards the prevention of interruption of service, and also isolation and location of electrical disturbances, before they develop to be of a general nature. This calls for not only the general design of the apparatus, but also the best possible operation of the circuits and switching equipment. The operation of any system, large or small, should be with a view to obtain the greatest economy of operation under normal condition, together with the least disturbance and most rapid re-establishment of service in the event of any accident or trouble in the station, on the transmission system. The switching equipment being the key of the entire system, the design of the control-board, and the selection and arrangement of the switchgear, calls forth special attention.

The following factors have contributed largely to the result reviewing the evolution of switchgear :—

(1) SPACE CONSIDERATIONS, which were brought into prominence by high building costs, for central and sub-stations in built-up areas. The difficulty in getting consumers to allow sufficient space for sub-stations, and the desire to increase the capacity of generating units in existing stations, have led to condensed forms of switchgear.

(2) STABILITY.—The dependence of large industries on the public supplies has increased the demand for reliability and continuity. This factor has contributed to the introduction of di-electrics, having a greater stability than air.

(3) PROTECTION TO LIFE has been increased by the Home Office Regulations and "safety first" propaganda, resulting in the encouragement of draw-out switchgear.

(4) LOW COST.—The demand for cheap electric supplies has been the main factor in the development of factory-built control units.

553. Functions of the Switchgear:—The switch-gear in any power scheme serves the following functions:—

(1) To collect electrical energy from the individual generating sets and centralise it to bus-bars.

(2) To distribute the electrical energy to the feeders from the bus-bars

(3) To control the electrical energy at various points of the system by connection and disconnection of the circuits at will.

(4) To disconnect any faulty section and provide continuity of supply to other healthy portions.

(5) To interrupt or prevent heavy short circuits.

The switchgear fulfils its most important functions, when conditions are abnormal, and these relate more to the system to which it is connected than to the unit of the plant controlled

554. Types of Switchgear:—

Switchgears fall broadly into three classes:—

(*a*) Those intended for low and medium-voltage service

(*b*) Those intended for high voltage service.

(*c*) Those intended for extra-high-voltage service.

The various types of switchgear may be briefly enumerated as follows:—

1. Open floor-mounting type.
2. Cubical type.
   (*a*) Panel-mounting.
   (*b*) Metal-enclosed stationary.
   (*c*) Metal-enclosed truck.
3. Cellular type (brick or concrete).
4. Metal-clad type.
   (*a*) Stationary.
   (*b*) Draw-out.
      (*i*) Horizontal.

(*ii*) Vertical.

5. Out-door type.
   (*a*) Open floor-mounting.
   (*b*) Cubical floor-mounting.
   (*c*) Polemounting.

Open cellular type of switchgear was introduced by Dr. Ferranti in 1894, to eliminate the earthed metal work near the high-tension conductors. But this scheme proved dangerous to the attendant, was non-fireproof, and only suitable for small amount of power. The panel-mounting type was next evolved. The scheme provided all high-tension gear behind a flat back-control panel, thereby protecting the attendant during switching operation, but did not provide sufficient protection while cleaning and repairing the oil circuit breaker.

Then came the brick or concrete-walled cellular-type switchgear, requiring greater space for accommodation thereby increasing the cost for housing ; because of its greater cost and lengthy time for erection non-portable factory built, portable steel cubicle-type was adopted.

With the ever-increasing size of apparatus, the stationary cubical-type has been changed to truck-type cubicle. This type of gear can be withdrawn from the live parts for inspection and repair. The draw-out, as applied to the steel cubicle, was introduced in 1903. This type of gear increases the safety to the operator.

The oil or compound-filled gear was first developed in 1905

The most recent and the best type of switchgear is the oil or compound-filled metal-clad gear. They can be either horizontal draw-out or vertical drop-down type.

555. The selection of switchgear :—Therefore, is dependent upon its operation under abnormal conditions, such as,

(*a*) ability to stand thermal effect of short-circuit current,

(*b*) ability of the parts to withstand the electro-magnetic forces due to short-circuit currents,

(*c*) ability to break the maximum short-circuit power, the system can furnish at its particular location,

and (*d*) ability of the insulation to withstand the surges created by the interruption of short-circuit current.

556 Actors are to be considered in selecting the suitable type for any class of work :—

1. Immunity from break-down due to following causes :—

(*a*) Surges.
(*b*) Vermin
(*c*) Dust, dirt, and moisture.
(*d*) Explosion.
(*e*) Thermal and electro-magnetic effects on short circuit

2 Protection of life of operator.

3. Location of faults and reduction of fire risk.

4. Facilities for inspection and repairs to circuit breaker.

5. Free from difficulty to control for normal switching operation.

6 Space occupied.

7. Time taken for erection.

8. Facilities for carrying out expansions and modifications.

9. Facilities for the installation of a spare circuit breaker.

10. Cost.

11. Portability.

557. Comparison of switchgear :—The following fundamental features require attention.

1. Insulation.
2. Isolation.
3. Enclosure
4 Interlocks.
5. Location.
6. Control.
7. Selection of isolation and transfer-switches.

1. **Insulation** :—The following three kinds of insulation are generally used for switchgear —Air, oil, or compound. Air is an unstable di-electric. Vermin, dust, dirt, and moisture play their important parts with the air-insulated switchgear. The difficulty has been overcome with the introduction of oil and compound insulation. The oil or compound is more stable, as they have got greater spark-lag than that of air and they have higher di-electric strength to withstand voltage surges on the system. So, oil or compound-filled gear requires comparatively less space than that of air-insulated gear. Oil is self-healing after break-down, and with commercial oil, the voltage required for a second break-down is increased due to drying of the oil.

The container for oil or compound acts as a guard against the accumulation of dust and dirt and the absorption of moisture. All gears are liable to accident due to explosion and so the tank, etc., of the switchgear must be made strong enough to withstand such explosive forces. The electromagnetic forces vary inversely as the distance between the conductors ; so that with smaller spacing employed in filled-gears, the forces are greater than those of open-gears. This requires greater strength of support, etc. The accidental contacts between live contacts are impossible with filled-gears. They do not require much cleaning or repair, and so are less liable to accidents.

The initial cost of oil-compound-filled gears with complete interlocking arrangements is cheaper than similar air-insulated gear. But air-insulated gears are without interlocking devices. Air-insulated gears deteriorate more than oil-compound-filled gears.

In compound-filled gears, there is a lack of accessibility of the current-carrying path. So only the bus-bars are compound-filled. It is difficult to carry out extensions with compound-filled gears without interruption of service, but no hinderance comes on the way in the case of air-insulated or oil-filled gears. Oil has another greater advantage that it has got, a greater cooling-effect than either air or compound. With reference to

cooling effect, they stand in the following order—Oil, air, compound.

From all considerations stated above, we see that oil and compound have greater advantages than air. Air can be used for low voltages, oil can be used for all voltages, whereas compound has got very limited use.

2. Isolation:—All types of gear must be provided with some means of isolation to carry out inspection, cleaning, and repairs of breakers, apparatus, relays and instruments. It was found till 1914 that most of the accidents, which occurred, was due to cleaning, repairing and handling of the apparatus, supposed dead. From that time draw-out interlocked gears have become popular and accidents are much reduced.

Two methods of isolation are generally used :—

1. *Stationary Method*.—The breaker or any other part, when isolated by means of isolating-devices, remains at its normal position.

2. *Draw-out Method*.—The breaker or any other parts are withdrawn from the live part of the gear.

In either of the cases the isolating devices must be provided on both sides of any part which requires periodic inspection, and which is liable to be damaged by accident.

There are two draw-out methods, *viz.*, vertical and horizontal.

The vertical draw-out method requires less floor space, and can be opened and inspected without encroaching upon the passage way. But this method cannot be applied to all types of gear, whereas a horizontal draw-out method, though requires more floor space, can be universally applied to all types of gear. The plug and socket arrangement had some difficulty in the draw-out gears, but entirely satisfactory results were obtained by the introduction of self-aligning features. The main advantage is that, when the breaker is withdrawn, it is definite that the breaker is dead. Such a certainty can never be obtained with stationary method. In case of inspection or repair of draw-out gear, the supply can easily be regained within a much shorter period by

replacing a spare in the position. It is easier to provide interlocking devices with draw-out gear On withdrawal of the gear the contact points are automatically closed by shutters, thus preventing accidental contacts with live parts. With stationary parts, reliance has to be placed on the human element.

The draw-out system is 7 to 10 per cent. more costly, but is not so costly as the completely interlocked stationary system.

3. **Enclosure**:—The following enclosures are generally in use:—

1. Open—Indoor, outdoor.
2. Metal enclosed—Cubicle, metal-clad.
3. Masonry enclosed—Cellular.

Open.	Metal-enclosed.	Masonry-enclosed.
1 No protection to life of the operator.	1. Definite protection as metal-encloser can readily be earthed.	1. Being semi-insulator, is not quite so safe to handle
	2. Flash-over to metal is a dead earth and will be maintained till the fault is cleared by protective gear.	2. The arc will probably be extinguished after the pressure-rise subsides, unless the arc strikes the earthed metal.
Note.—For voltage above and including 22 K.V. open-type is preferable. The ultimate cost of open-type of gear for high voltages is less, because the	3 No risk of attendant in touching the metal parts	3 Risk to attendant in touching the metal parts.
	4 Requires less space.	4 Requires more space.
	5. Erection-cost is less, because it is factory-built.	5. Erection cost is nearly three times that of metal enclosed.

Open.	Metal-enclosed.	Masonry-enclosed.
building is not necessary. Hence where open space is available at lesser cost, open gear should be preferred for extra-high voltages.	6. Self-contained, portable, and easily removed for inspection and modification.	
	7. Interlocking is easier.	7. Interlocking is difficult.
	8. Less costly.	8. More costly.

According to Indian conditions, where open spaces are available without much cost and trouble, open outdoor gears should be selected for voltages above and inclusive 22 K. V.

For voltages below 22 K.V. and which can be directly and economically generated, metal-enclosed draw-out gear should be selected.

Of the metal-enclosed type, cubical gears were universally used till the introduction of metal-clad gear : all other gears are slowly decreasing in application and we think that in the long run metal-clad gears will be universally used. Metal-clad gears are constructed for every range of voltage up to a maximum of 35 K.V.

The *relative advantages of the metal-clad* gear are various and the few important of these are summarised below :

1. The oil or compound is used for insulation.
2. All conductors are embedded in compound or immersed in oil, and this feature, combined with total enclosure of all parts, ensures safety and eliminates the possibility of break-down due to rats, mice or other small vermins.
3. The total enclosure of all parts reduces the amount of cleaning and attendance required, and thus reduces the maintenance costs.

4. The design of the equipment requires the interchange of breaker only. A spark breaker can be interchanged within a very short time.

5. Economy of floor and building space is obtained by compactness of the design.

6. It can withstand the rough usage and arduous service.

7. The advantage of better portability is obtained.

8. It is more suitable for tropical climate.

9. Interlocks are more easily provided

10. Manual operation can be totally eliminated.

The metal-clad gear is built on the unit principle, so that one unit can be erected singly or in a number, bolted together to form a switchboard. Each unit consists of :—

(*a*) The fixed portion consisting of the supporting structure, bus-bars, current transformers, voltage transformers with its isolators, cable box, plug members of the main isolator, circuit-breaker-operating mechanism, etc.

(b) The movable portion—oil circuit breaker, and the socket members of the main isolator

Vertical drop down of circuit breaker is only applicable with the metal-clad gear. It can be isolated by horizontal draw-out method too.

Vertical *vs* **Horizontal Isolation** :—1. Vertical method requires less floor area. Inspection, etc., can be done without encroaching upon passage way.

2. Vertical one can easily be adopted for duplicate bus-bars

4. Interlocks :—The most frequent mistake on the part of the operator is to open the isolator of any line-carrying load. Interlocking of the isolator, with the main oil circuit breaker, prevents the opening of the isolator without tripping the main oil circuit breaker. For draw-out type of switchgear, the interlocking should be such that the switchgear cannot be drawn out, until and unless the oil circuit breaker is in off position. Indicating lamps or any other devices should be provided to inform the operator the on and off-positions.

Interlocking devices must be provided in the neutral earthing switches of alternators or transformers so that more than one machine cannot be earthed at one time.

Sometimes interlocks are provided in the earthing devices of feeder at both the ends. Operator making the earthing connection of a feeder at one end cannot be at both the ends at once, and has, therefore, to rely on a second party to see that the feeder is dead from the far end. Faults due to operation cannot occur, if interlocks are provided. This is a costly arrangement. If such interlocking is employed, it must be electrical.

When the isolated apparatus is earthed before being handled, it must be impossible to re-close the isolating device until this earth has been removed.

5. **Control** :--It is difficult to give any accurate recommendation as to the method of control for any plant. In general, it may, however, be said that the direct control of the switchgear can be adopted for voltages upto 6,000 volts and the plant capacity not exceeding 5,000 kilowatts. For higher capacities and voltages, it is advisable to mount the oil circuit breaker in compartments and control it from a distance

The followings are the main *consideration for remote control of circuit breakers* :—

1. The attendant must have full self-control, if he is to act promptly in case of emergency. This is only possible by removing the high-tension gear from the point of control.

2. With large sizes of plant, there is a likelihood of explosion and other troubles, hence remote control increases safety to operator.

3. With remote control the switchgear can be located outdoor or in a fire-proof building and the control room near the generators.

4. The instruments and low-voltage apparatus can conveniently be mounted on a separate control-board.

There are two methods of remote control in general use :—

1. Mechanical remote control, and
2. Electrical remote control.

When the breakers are not large enough, and they can be located near the control-board, mechanical control may be suitable. If the automatic trip-coils are fitted with the breaker itself, the inertia of the levers and connecting rods will reduce the opening speed of the breaker. The final pressure at the contact points, when the breaker is connected to the circuit, is reduced due to the back-lash in the mechanical driving system. This decreases the current-carrying capacity of the brush contacts.

Absolute isolation of the high-tension equipment may be secured with the electrical control, which, thereby, largely eliminates the personal hazard and danger of accidental contacts and makes possible the use of the minimum amount of high-tension buses inside the station. With electrical operation, the control-board is condensed to minimum The breaker may be either solenoid or motor-operated. The solenoid operation is cheaper, if D. C. is available. Otherwise, it is necessary to install battery equipment.

It is desirable to have some form of indication of the operating position of the remotely controlled switchgear at the control-board. Such indications can be obtained by lamps or semaphore indicators. In some cases dummy diagram of the whole switching scheme is mounted above the control-board.

6 Selection of Isolation and Transfer Switches:—

Duplicate bus-bar system is generally used at present. The methods used for such a scheme are the following :—

1. *Air-break Isolating Switch :*—It is used for stationary type of switchgear. In almost all cases the operator is to enter the switch room and to expose to high-tension conductors in order to operate them.

2. *Change-over Plug :*—It is applicable to draw-out gear only. In order to transfer the circuit from one set of bus-bars to the other, it is necessary to withdraw the breaker, change over the bus-bar isolating plugs of which only one set is provided, and the re-insertion of the breaker. Quick transfer circuits, in case of emergency, is impossible with this scheme. The main advantage of duplicate bus-bar system is lost and bad operation may happen in hurry.

3. *Oil Isolator* :—It can be applied to all types of switchgear. The selector switches can be operated externally and are easily interlocked. They are applied generally to metal-clad gears. Duplicate blades can be provided and can be transferred without breaking the load when used in conjunction with bus-coupler.

4. *Double Circuit Breaker* :—This scheme can be applied to all types of gear. This is the best scheme, but it is not universally adopted because of its greater cost. It affords the following advantages :—

(*a*) It is not necessary to enter the high-tension room except in case of inspection, repair, etc.

(*b*) It is possible to supply energy in case of failure of one of the breakers.

(*c*) It is not necessary to employ a separate bus-coupler.

(*d*) Immediate transfer of circuits from one set of bus-bars to the other is possible without difficulty.

558. Conclusions :—From an analysis of the fundamental features of the various types of high-tension switchgear, the following conclusions can be drawn :—

Insulation :—Both compound and oil show a distinct advantage over air The difference between compound and oil is not so marked, but the latter has advantages over the former. Oil can be used for all voltages, whereas the use of compound will probably have an upper voltage limit of 66 K. V.

Isolation :—Within its range of application, the draw-out method is preferable to the stationary method. Owing to the enormous size of the apparatus and difficulty in the design of satisfactory plug and socket bushings, the limit of the draw-out method will probably be in the neighbourhood of 66 K V.

Enclosure :—Metal-enclosed gear is preferable to either masonry or open.

Interlocks :—Complete interlocks are demanded by modern conditions and are essential both for safety and continuity of supply.

Location :—Indoor gear is preferable for all voltages, but, for 44 K V. and upwards, outdoor gear has an application where cost is of prime importance.

Control : – Remote electrical control is the most flexible system and for all large schemes, it is essential. Remote mechanical and direct control has a limited application.

Bus-bar Selection : – Double breakers are preferable to all other methods. In the order of efficiency the remaining methods may be placed as follows :— Oil isolators, air-break isolating switches and change-over of plugs.

559. Maintenance of the Switchgear :–

General :— Where switchboards cannot be shut down periodically, inspection and cleaning should proceed in section which can be made dead, as opportunity occurs. A log of all the inspections, showing the date, parts inspected and cleaned, lubricated and checked, etc., is maintained, and also, where adjustments carried, are logged

Cleaning :—When cleaning switchgear or switchboards, cotton-waste should not be used, as loose fibres, metallic impurities, etc . are liable to be left behind corners, etc., and may subsequently cause break-down. The cleaning cloths should be of strong firm fabric. All insulators, whether porcelain, bakelite or other material, should be kept scrupulously clean and dry. Polished slate and marble are cleaned with a damp cloth and polished with a dry cloth and must not be touched with any oily rag. Lubricating or mineral oil must not be used. Metal-polish also should not be used.

Lubrication :—Moving parts of operating mechanism, connections between auxiliary switches, interlocking gear, trip gear, etc , should be oiled, where necessary, and should be operated several times to ensure that the mechanism works freely; surplus oil should be wiped off.

Connections and Small Wiring : – Connection clamps and joints, cable-eye fixing bolts, secondary wiring, terminal bolts, earthing terminals should be periodically examined and tightened.

Circuit Breakers :—Circuit breakers should be closed and opened several times at each inspection. A specially thorough inspection should be made after operation under abnormal conditions.

Operating and Tripping Mechanism :—All trip coils, closing or tripping relays, closing solenoids, etc., should be tested regularly. All bearings and rubbing parts should be periodically lubricated (separately given).

Relay and Auxiliary Switches :– Contacts of relay and auxiliary switches of the self-cleaning and wiping type may be kept slightly greased with vaseline. But contacts, however, must be kept scrupulously clean and dry, and must, on no account, be kept greased. Examine the contacts of the apparatus which operate very frequently with a view to provide renewals in good time

Isolating Switches and Knife Switches :—Contacts should be kept clean and slightly greased. The contact pressure is self-adjusting and should not require any alteration.

Interlocks :—They should not be put out of action even temporarily, unless absolutely necessary. Interlocks are substantially constructed, but they may become an actual danger, if, for any reason, they are left inoperative.

Instruments :—These are sealed and do not require any special attention. They may be recalibrated without breaking the seal, and the zero point may be adjusted. If faulty readings are suspected on the instruments with potential circuits, examine the small wiring fuses, on the H. T. side of the potential transformer. If ammeters or any other instruments operating off current-transformers, are disconnected for any reason, the leads from the current transformer should be joined so as to short circuit the corresponding current transformers (given after).

Instrument Transformers :–The oil-level in the potential transformer should be maintained as per instructions on the cover plate of the filling, opening on the top of the transformer. The oil should be replaced every two or three years, or the old oil may be filtered and used again. Current transformers should never be left

open-circuited on the secondary side. Although the current transformer may stand this without damage, it is likely that their accuracy may be impaired owing to excessive magnetisation of the core.

Shunt and Series Regulator :—Keep the operating mechanism lubricated. Note that the guard tube for the remote control is firm. Adjust the tension of the chain. See that the regulator contracts are clean and are not pitted. If any discolouration is noted, check the pressure of the brushes, and, if necessary, increase the pressure. The contacts should be kept slightly greased.

Auxiliary Supply :—The battery is used and this should be kept in accordance with the instructions given by the makers ; the supply being to such apparatus as trip coils, relays, interlocks, etc., which are seldom used, these should be caused to operate at every inspection to ensure that the auxiliary supply is in order.

PROTECTIVE GEAR

560. General Review :—The expression "protective gear" refers to apparatus so constructed and connected as to protect automatically electrical machinery, switchgear and conductors, from damage due to excessive currents flowing through them, defects in their insulation or other abnormal conditions. Protection in general is the most essential and the first thing to be considered at any system. In large power station and high-voltage systems, where an attendant or an operator has to look after many things, cannot attend to all the working machinery at a time. To avoid any such danger and damage to the machinery which costs a good lot either for a repair or renewal and interruption of service, automatic protective devices must be adopted.

561. Development of Protective Gear :—It is interesting to survey the development of protective gear from the earliest times, since, by this means, a very definite idea of the general possibilities and uses of such gears may be obtained.

In the earliest days of electrical supply, only very small installations were at work which consisted of dynamos of low output supplying power to a few lights or

possibly small motors. On such an installation it was found that short circuit on the system or an overload would cause damage to the dynamo or other apparatus, and such damage was often difficult to locate and costly to repair.

In order to protect the dynamo against damages caused by excessive currents and to make easy the location and repair of fault on the distribution system, the earliest form of protective gear, *the fuse*, was adopted, the effect of which was simply to create a definite weakest point in the system which was readily accessible and renewable. The fuse still holds a place of considerable importance in protective gear, since it is cheap and reliable, but when the capacity of the circuits increased to such an extent that fuses were found expensive in replacement, certain forms of automatic overload protection were evolved which would disconnect the circuit on the occurrence of an overload without necessitating the replacement of any apparatus.

Such devices were originally instantaneous, and a further step in the evolution of protective gear was taken when overload devices, having an inverse relay characteristic, were adopted.

Overloads of considerable magnitude, if they are maintained for only a very short interval of time, do not necessarily cause damage to plant or cables, and it was early found desirable that some form of protection should be utilised which would discriminate between momentary overloads and continuous overloads ; in other words, it became necessary to imbue the overload protection with what may be termed "intelligence," and various forms of inverse time-limit overload protection were evolved.

With generating and distributing systems increasing in size, the feature of discrimination in protective gear became of primary importance, and it became necessary to provide apparatus having "intelligence" in another direction, the feature required being to minimise the area disconnected automatically, as far as possible, and, in so doing, to preserve continuity of supply to as much of the system as possible.

To this end, various types of balanced protective gear have been evolved, and also overload relays have been produced, which have a definite time-limit independent of the degree of overload, or an inverse time-limit with a definite minimum value.

Relays with definite time-limit are used in some cases in order to minimise the amount of power in the circuit which has to be disconnected when a short circuit occurs. When an alternator is short-circuited, the current output will be very heavy, reaching, in about 1/20th. of a second, the value of approximately 17 times normal output. Subsequently, the value of current will be rapidly reduced until, after a lapse of 3 or 4 seconds, it will attain a steady value of approximately twice the normal output.

A relay with a definite time-limit will not cause the circuit to be opened when the current is at its maximum value, but will delay operation until more favourable conditions occur for the opening of the circuit.

Considerable damage has been done, even during the short period of time, which elapses when a definite time-limit relay is used and the various forms of balanced protective gear and others which operate only under faulty conditions are designed to operate immediately so as to minimise damage to apparatus.

Overload protection, as applied to alternators, was satisfactory when each installation had only one machine, but with modern installations, where many machines run in parallel, it has been found desirable to confine the protection (overload) to the distributing system. If an overload occurs on a system supplied by a number of machines in parallel, each of which is equipped with overload protection, the result will be to disconnect the whole of the machines from the system, while, if the protection is on the distributing system only, that part which is affected will be disconnected. For this reason, the protection of machines is now considered to be more effectively dealt with an adoption of balanced protection in combination with reverse protection, the latter form of protection being such as to intelligently discriminate between the conditions which occur when the machine is abnormally receiving power.

562. Functions of Protective Gear :—The essential function of protective gear may be stated as being :—

(1) to prevent damage to the protected apparatus,
(2) to maintain continuity of supply,
(3) to minimise the area shut down under abnormal conditions,
(4) to disconnect apparatus with the minimum of disturbance to the system as a whole.

563. Desiderata :—The chief features which should be possessed by an ideal protective gear are as follows :—

(*a*) Certainty of repeated operation under the abnormal conditions against which it is designed to protect, and certainty of non-operation under any other conditions whatsoever.
(*b*) Discrimination.
(*c*) Rapidity of operation.
(*d*) Reliability resulting from correctness of design and robustness of construction.
(*e*) Simplicity.
(*f*) Low initial cost and low maintenance charges.
(*g*) Easy adjustment and testing.
(*h*) Adaptability to existing system.
(*i*) Adaptability for extension without alteration to existing protective gear.

The system which possesses the greatest number of the above characteristics under any given conditions should be considered the best.

564. Technical Considerations Regarding Various Methods :—The methods of protection of high-pressure systems have wholly occupied the attention of the electrical engineers all over the world, and various improvements are being effected in the design and working of the various protective devices. At the present day, protection is applied to the electrical system for the purpose of minimising the interruptions to serve and the damage to apparatus, which results from abnormal conditions on the system. The protective equipment for each individual line or piece of apparatus should either act independently without affecting or being affected by the

rest of the system, or should be properly co-ordinated to form part of a comprehensive system fulfilling the requirements stated above. A properly-designed system of protection should maintain service under all conditions, unless this is definitely prevented by the lay-out of the system.

In most cases, the function of the protective device or relay is to disconnect the faulty apparatus or line from the remainder of the system before the trouble can spread, and to do this with the least possible disturbance of service. It is not always possible to clear a fault without interrupting service. For example, if a fault develops in a branch or radial feeder, which is the sole source of supply of load, or a single generator supplying a system develops troubles, it is obviously impossible to prevent an interruption. However, since most systems have more than one source of supply, and since important loads are ordinarily supplied by more than one feeder, it is usually possible to maintain continuity of service.

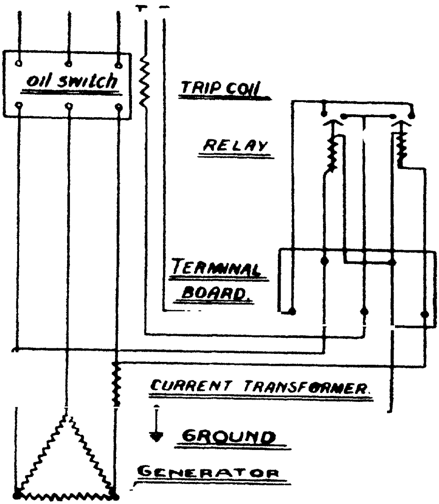
The main principle of these devices is that they automatically and immediately cut out the plant supplying power to the faulty lines and even has the discrimination to adjust before actually operating.

The protective devices can be classified under one main heading—**Relays.**

565. Relays :—These may be defined as protective devices used in connection with circuit-breakers to disconnect any part or section of a system on which a fault occurs, but leave the rest of the system in operation without being further affected by the faulty section. They are either alternating or direct current and are used to protect circuits and machinery from the effect of overloads, underloads, short circuits, reverse currents, high and low voltages, and such other abnormal conditions. In general, a relay consists of, *first*, a coil, or system of coils connected either directly in series or in parallel with the circuit controlled ; *second*, a relay consists of a movable part such as a plunger or a revolving disc, whose travel is controlled by the relay coils, and *third*, of a contact device which is actuated by the movable part and which

controls the operating circuit, such, for instance, as the trip coil of the circuit-breaker to which it is connected.

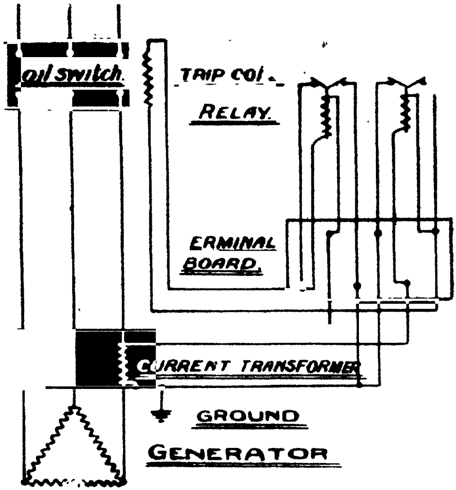
Relays of both A.C. and D.C. are similar in their principal characteristics and may be classified under two main headings: (1) Circuit Closing, and (2) Circuit Opening. The function of the former is to close an electrical circuit, usually D.C., through a trip coil on an oil-switch or circuit-breaker, or it may short-circuit a low-voltage release coil and thereby open the oil-switch or the circuit-breaker on the occurrence of the condition upon which the relay is designed to operate.



Connections of Circuit-Closing Relay.
Fig. 10.04

Circuit-closing relays are equipped with carbon contacts which will open 10 amps. with 110 volts. Where the operating circuit is above 110 volts, an auxiliary switch should be used in series with the relay contacts to open the circuit. The function of a circuit-opening relay is to open an electrical circuit usually A.C. and thereby cause the oil-switch or circuit-breaker to open by the use of trip coils in the secondary of current transformers or by low-voltage release coils. *Circuit-openning relays* are equipped with quick-break contacts which open independently the time of travel of the plunger. With these relays the trip coils of an oil-switch or ciacuit-breaker must be set somewhat lower than the setting of relay so as to ensure positive action.

566. Types of Relays:—There is a large number of different types of relays in use on power transmission



CONNECTIONS OF CIRCUIT OPENING RELAY.

Fig. 10'05.

systems, according to the type of protection required of them.

(1) Overload protection.

(2) Differential protection.

(3) Directional protection.

(4) Under and over-voltage protection.

(1) Overload Relays:—These may be *instantaneous*, *definite time-limit*, and *inverse time-limit*. With *instantaneous relays*, the contact device will operate immediately and close the tripping circuit of the breaker when the abnormal conditions, which the relay is to take care of, make their appearance and start the moving part of the relay. When *definite time-limit* relays are used, there is a definite time delay imposed between these two movements. With *inverse time-limit* relays, the time delay is inversely proportional to the magnitude of the disturbance.

For instantaneous overload relays the *plunger type is the best*—Fig. 10·07. Inverse time-limit relays may be either of the below type or the induction type—Fig. 10·09.

Instantaneous or Current-limiting Relay:—A coil of wire, having a movable plunger (iron core) at its centre, is an over-load relay in its simplest form. When an electric current of sufficient magnetising power flows through the coil, the plunger is drawn up. As it is drawn up, it may be made to strike against the tripping toggle of an oil-switch, or close two contacts whereby the tripping coil circuit is energised. There is a current-setting device by which it can be made to operate for any desired value of current. This simple type is used only on small switches and is not desirable in the larger ones. And this type of relay is instantaneous in action and can be used either for closing the circuit or opening it. When the current in the main power circuit becomes larger than the value for which the relay is set, as it would be in the case of short circuit in the line, the current in the secondary of the transformer would also be above the normal and the coil of the relay would pull up its plunger. When the plunger moves upwards, it closes the two contacts, which, in turn, close the tripping circuit, and oil switch opens suddenly, thus protecting the circuit and the machinery from large short-circuiting current.

Construction:—Fig. 10·06 shows the construction of this relay. The coil *c* is connected in the circuit carrying the current which is to operate the relay. The movable plunger *a* carries a disc contact *d*, which is held in position by a spring and a collar on the plunger rod. The plunger is limited in its upward movement by stop *b*, the position of which can be adjusted by the thumb screw *e*, and in its downward movement by stop *f*, which is also adjustable by means of the screw *g*, which allows the stop to be moved up or down the full length of the slot.

Operation:—The current coil *c* produces a flux in the iron circuit formed by the frame and the iron pole piece; and the iron plunger is attracted to the pole piece. The current required to lift the plunger depends

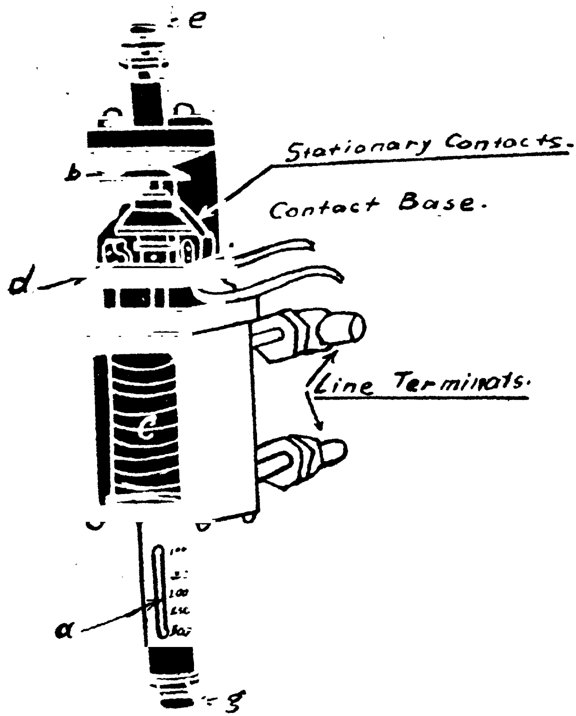


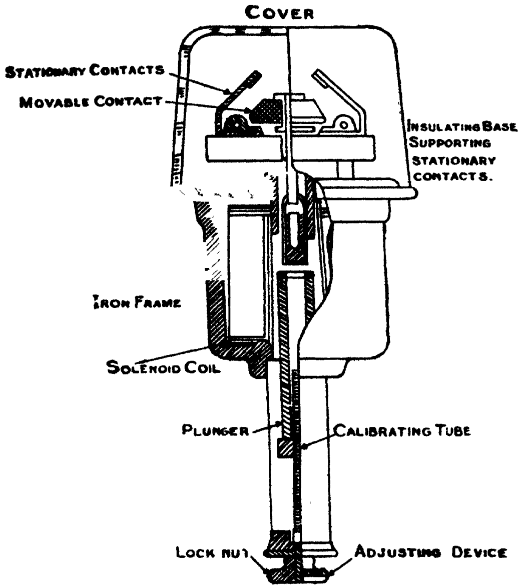
Fig. 10'06

Current-limiting Relay.

on its distance from the pole piece, which can be adjusted. When the plunger picks up, it is prevented from coming into contact with the pole piece by stop *b*. The minimum current required to hold the plunger in its up-position depends on its distance from the pole piece, so that the current at which the plunger will " drop off " can be adjusted by altering the position of stop *e*. The " pick up " and " drop off " of the relay are, therefore, adjusted by the current-limiting relay.

A pointer attached to stop *g* indicates on a scale the " pick up " current and a line round the circumference of thumb screw *e* indicates on another scale the " drop off " current.

Inspection :— See that the plunger moves freely in its guides. The fixed contacts should periodically be slightly turned to a new unturned surface to the contact disc ; the latter should be



Sectional diagram of plunger type current limiting relay.

Fig. 10'07.

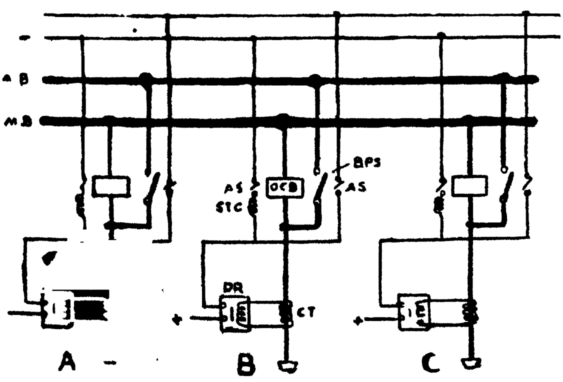


Fig. 10'08. Connection diagram.

loose on the spindle, so that it will be safe aligning with the two fixed contacts. The lower and upper stops should be adjusted to give the desired "pick up" and "drop off" current.

Definite Time :—A second protective principle, which is of immense value, is the definite-time over-current. This principle is usually used in combination with the preceding one to give the familiar inverse definite minimum time-relay. Protective devices, operating on this principle, have inverse time characteristics upto a certain value of current, while at all higher values they operate at a certain definite minimum time. Such devices are necessary when there is no branching of a circuit at the junction of the faulty section to the rest of the system as in a radial or tandem system. In applying this principle, the protective devices at the different points have their definite minimum times adjusted, so that with the abnormal values of current they operate in a definite order, beginning with the one farthest from the generating station, the longer it will be allowed to remain on the system There is, of course, a limit to the number of sections that can be thus protected, since from $\frac{1}{4}$ to $\frac{1}{2}$ second must be allowed between settings for consecutive sections, and the maximum time-setting must be short enough to prevent a fault from unduly affecting the entire system or part of it.

Direction of fault current has also been used in a great many protective schemes as a criterion both of abnormal conditions and of location of the fault. Analysis of a system will show, in a great number of cases, that the normal current in any section is in one direction, and a fault causes a reversal of the current in the faulty section but in no other part of the system. Both sensitiveness and selectivity may be obtained by using a directional element, which prevents the protective device from operating in the normal direction of the current, and permits a relatively low setting for currents in the direction opposite to normal. In the practical application of this principle. there are two difficulties to be overcome. The first is that the direction of current in an A. C. system means the vector relation between

current and voltage. Hence, to apply the reverse-current principle, potential must be introduced as the base of reference. It has been suggested to use, as a reference, a current whose direction is fixed, such as, the fault current in a grounded neutral. This scheme is not used very extensively and the potential is ordinarily the standard of reference. Since, under abnormal conditions, the voltage may fall to a low value, it is necessary to make the directional element very sensitive. The second disadvantage arises from the fact, that transients may occur resulting in a momentary reversal of power. To overcome these disadvantages, it is usual to combine a very sensitive instantaneous directional element capable of operating on very low values of voltage with an over-current element having time characteristics. Such a protective combination is very useful.

Inverse-Time Over-Current Relay :—As a refinement of the instantaneous over-current principle, there was developed the inverse time-limit principle, in which the time of operation of the protective device varies approximately inversely with the magnitude of the current. The advantages gained by the application of the principle are two-fold. First, the current settings may be made lower and sensitiveness thereby increased, since the normal transients may be large enough to start the operation of the protective device, but will not last long to complete the operation. Under abnormal conditions, if a fault produces a slight over-current for a short time, the protective device operates. Secondly, selectivity may be obtained with fewer parallel paths than when operation is instantaneous, since, even with abnormal values of current, a difference between the values in the faulty section and the other parallel paths feeding it, may make an appreciable difference in the time of operation of relays at the various points and permits the faulty section to clear before the other sections have operated.

Over-current Inverse-Time Relay (Induction Type) :—

A. Aluminium disc with shaft pinion control spring for 60 relays.

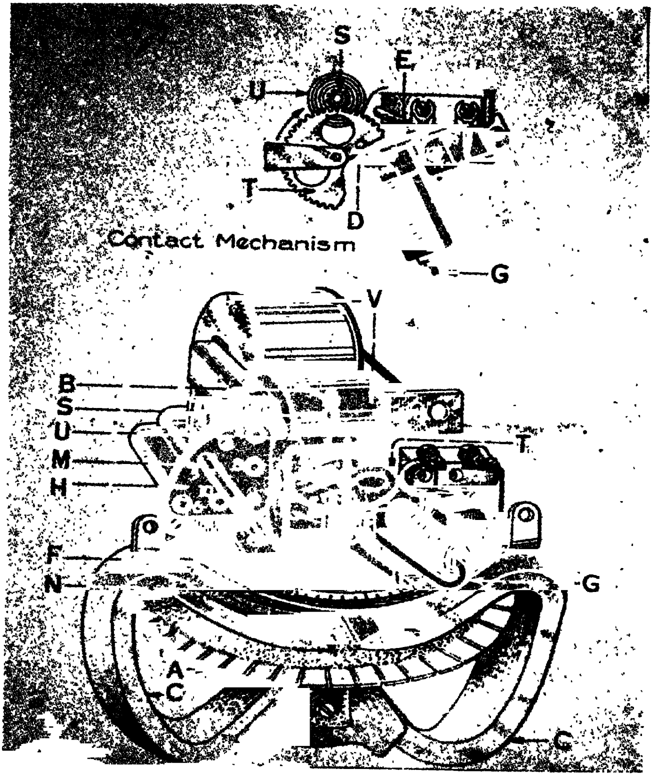


Fig. 10·09.

Induction-Type Inverse-Time Over-Current Relay.

A. Copper disc with shaft pinion control spring for 25, 40, 42 and 50.

B. Top bearing.

C. Permanent magnet complete.

D. Contact with tip (inner).

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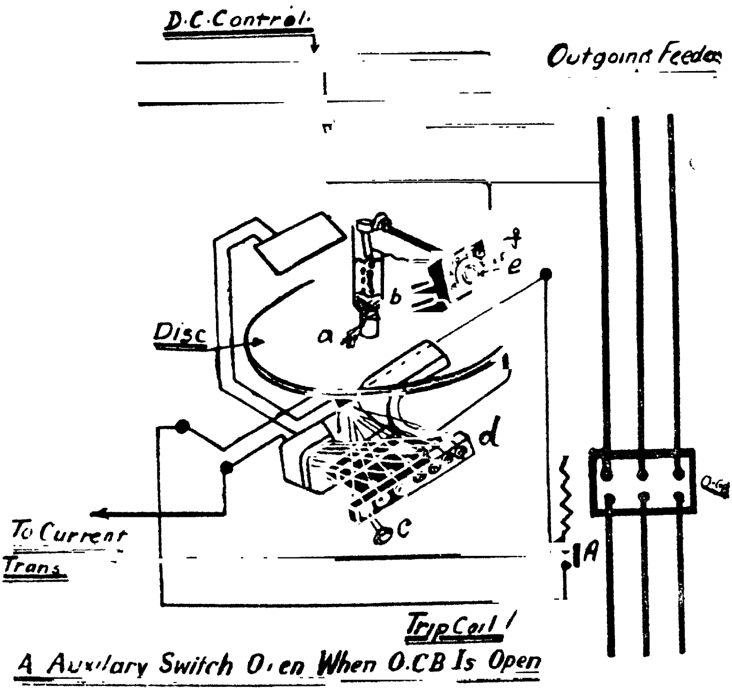

Inverse-time Over-current Relay, Internal Connections.
Fig. 10'09A.

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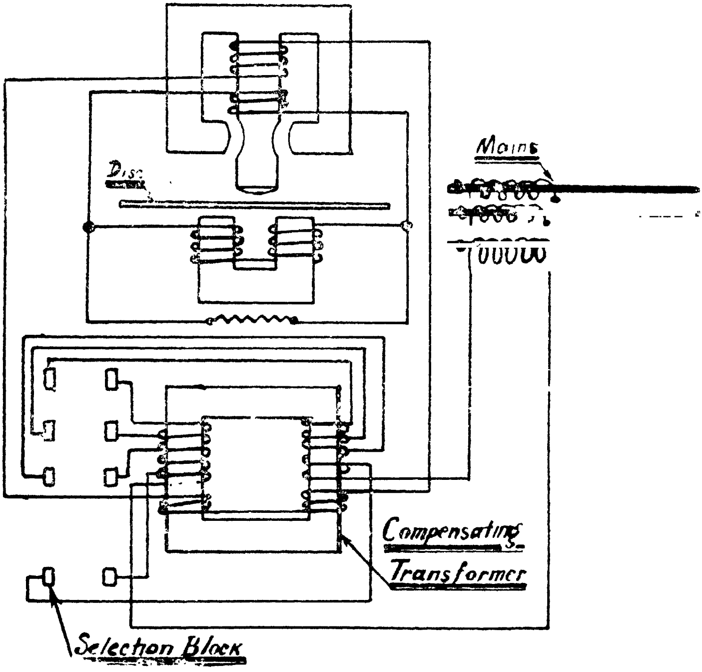


Inverse-time Over-current Relay, External Connections.
Fig. 10'09B.

E. Contact with tip armature and insulation plates.
F. Time-setting lever.
G. Holding magnet.
H. Current tap plate.
M. Current tap plug.
N. Time lever scale.
S. Time lever pinion.
T. Time lever contact gear.
U. Control spring.
V. Saturating transformer.

Construction and Operation of the Relay:—When an over-current occurs, the rotation of the disc, actuated by a U-shaped driving magnet *B* and retarded by a pair of permanent magnets *C*, causes the movable contact *R* to bridge the two stationary contacts after an interval of time, dependent upon the amount of current and the starting position of the disc as pre-determined by the setting of the time lever; the driving torque is produced by the phase-splitting action of the shading coil on the pole pieces.

The coil of the target magnet is connected in series with the tripping contacts. This magnet actuates a target and also increases the pressure on the contact. The opening of an auxiliary switch on the oil circuit-breaker releases the holding action.

Contacts :—The movable contact is a silver plate, mounted on an insulating block, which is under the great segment ; when the relay operates, this plate bridges the two stationary contacts which are mounted on flexible phosphor-bronze arms. The relay contact and target magnet are made from direct current tripping of the circuit-breakers. The contacts can carry 18 amps. of a D. C. current without being injured. But where heavier currents are necessary for the tripping of oil-circuit-breaker, auxiliary switches are installed.

An indicating target gives visible indication as to which phase of the circuit has tripped the circuit-breaker. It is reset by means of a nob pointing out of the glass-cover.

The Actuating Coil :—The actuating coil winding is mounted directly on the U-shaped magnet and consists of edgewise wound copper strip of large sectional area to prevent any considerable temperature rise. Leads are tapped in equipment from the ends of the coil in accordance with the ampere-turns required, and connected to the tap plate *H*.

Disc :—The disc is made of copper or aluminium. It is slotted to different depths to compensate for the greater pull of the spring as it rotates. The relay is caused to complete its operation, if started by the minimum current, unless this current falls to a definite percentage of its original value, which, although it may remain constant at that point, will allow the disc to be returned by the spring to its original position.

A black spot is pointed at the edge of the disc, the centre of this mark should come to the centre line of the bracket supporting the permanent magnets, when the time lever is set at zero. When the time lever is set at zero of its scale, the contact mechanism is brought into position for assembly with relay frame and the holding screws are partially set up leaving the gear and pinion disengaged. The disc is then rotated carefully in the counter-clockwise direction from its free position, through approximately 7/8 of revolution, until the spot painted on the edge of the disc is midway between the pole tips of the permanent magnets. The gear and pinion are engaged and secured by tightening the holding screws *S*.

Pole Pieces of Driving Magnet :—Both the upper and lower pole pieces of the driving magnet have a secondary conductor or shading coil. Thus, when an alternating current flows through the coil winding, a

distorted magnetic field is produced passing through the copper disk causing a torque to be exerted on the disc. The amount of this torque for a given frequency depends on the value of the current passing through the coil. The copper disc is equipped with a control spring to return it to its original position. In order to secure the proper time of operation, both the electro-magnetic and the permanent magnetic dampings are utilised, the desired time-current curve being obtained by a proper combination of the two.

Relation between Disc and Permanent Magnet :—The permanent magnets at the front of the relay serve as a retarding element for the disc. They are adjusted on the magnet shoe, so that the relay will close its contacts in 2·2 seconds, when 80 amperes at rated frequency will flow through the relay current studs; the time lever set at 10 and the current tap plug is placed in the 4 amperes tap.

Numbers, indicating in arbitrary units the magnetic strength of retarding magnets, are painted on them. This is to replace them in case they get deteriorated.

Deciding Upon the Time-Setting :—The time's operation at moderate and severe over-currents is selected with due consideration to the nature of circuit protected. This is specially so when the relays are used for selective operation.

The time in seconds to trip, shown by index-plate (table below), is the time taken to close contacts, and, as it takes sometime for the circuit-breakers to open after the relay acts, allowance is always made for that. The setting of the relays for selective operation should be in accordance with the time-current characteristics.

Table.

Time-Current Tap-Setting.	Lever-Setting 1	2	3	4	5	6	7	8	9	10
1.5	1.0	1.7	2.6	3.5	4.5	5.6	7.2	8.8	10.8	13.6
2.0	0.7	1.1	1.6	2.2	2.9	3.7	4.6	5.5	6.7	8.3
3.0	0.6	0.9	1.2	1.6	2.0	2.5	3.1	3.7	4.5	5.6
5.0	0.4	0.6	0.9	1.2	1.5	1.9	2.3	2.7	3.3	4.0
10.0	0.3	0.5	0.7	0.9	1.1	1.4	1.7	2.0	2.4	2.9
20.0	0.2	0.3	0.5	0.6	0.8	1.0	1.2	1.5	1.8	2.2
30.0	0.2	0.3	0.4	0.6	0.7	0.9	1.1	1.3	1.6	1.9
50.0	0.1	0.2	0.3	0.4	0.6	0.7	0.9	1.1	1.3	1.6

Time in Seconds to Trip.

Take an example of setting relay.

Relay is to open the line on a sustained current not less than 450 amps. and is to open in 1·5 sec. on a maximum short-circuit current of 3,750 amps. primary-current tap-setting.

$$\frac{\text{Minimum primary current to open}}{\text{Current trans. ratio}} = \text{current tap-setting.}$$

$$= \frac{450}{\frac{60}{1}} = 7{\cdot}5 \text{ amps. use } 8.$$

To find the time lever setting to give 1·5 sec. delay at 3,750 primary current,

$$\frac{\text{Maximum short-circuit current}}{\text{C. T. Ratio.}} = \text{S. current}$$

$$= \frac{3750}{\frac{60}{1}} = 62{\cdot}5$$

Note that this 62·5 amps. is 7·8 times the current tap. Current tap setting at right or left, note 1·5 sec. delay will occur when the lever-setting is between 6 and 7.

The accuracy of relay is affected by the change on the frequency of the system. Therefore, relays used on the 25 ∿ supply cannot be used with 60 ∿ supply.

It is essential that the disc shaft should be set upright.

(2) **Differential Relays** :—The differential principle has found very wide application in recent years. Differential current is used most commonly and differential power in rare cases, whether normal or abnormal ; the current flowing into any section of a system. no matter how great in value, must equal that flowing always from it, so long as the section has no electrical fault within itself. The device for detecting abnormal conditions is arranged to balance the normal input current

or power against the output. It operates when any abnormal conditions, such as a short circuit or ground produces an unbalanced state of affairs. The transient current of transformers, or the power loss within the section, acts in the same way as a fault, but, of course, to a much lesser degree ; and these normal unbalances can be taken care of by the relay setting. A protective scheme operating on this principle, and applied to each individual piece of apparatus, or section of line, therefore, disconnects the faulty section, but is inoperative under normal conditions and when faults occur in other sections of the system. It does not detect faults that draw no current such as are open circuit or a ground on an ungrounded system ; and it must be set high enough to be inoperative on power losses or charging current within the section at abnormal current values caused by the external faults. Difficulties arise in the practical application of this scheme because, quite often, current transformers must be able to maintain a balance of all the way from partial load to 20 times full load. Trouble is also caused by unequal burdens placed on the current transformers by the leads of other loads and by improper impedance of the relay used to detect the unbalance.

A scheme similar to the differential one is quite often employed in which a balance is obtained in a similar manner out-lined already. But instead of the balance between the in-coming and out-going line-currents of a system element, it is a balance between two or more parallel paths, which normally carry equal portions of the total current. A fault does not usually involve all of these parallel paths to the same degree, and thus it alters the distribution of current between them. The protective device is arranged to be actuated by the difference between the currents in the several paths, and thus, operates from a fault in the section, but not under other conditions. Sometimes, special split conductor cables are used. Frequently, twin circuit lines are available Parallel windings in machines or transformers can similarly be protected. If the inherent impedance-unbalance of parallel paths causes a normal current to divide unequally,

relays can be provided which operate when the ratio of currents differs from normal. Selectivity between the parallel paths is easily obtained for three or more; but with only two paths directional relays are usually necessary. As a modification of this scheme, it is possible to arrange this relay to be actuated not on an absolute difference between the currents in the two parallel paths but on a percentage difference based on total value of current in conductors.

(3) **Directional Protection** :—Direction of the fault current has also been used in a great many protective schemes as a criterion both of abnormal conditions and of the location of the fault. Analysis of a system will show, in a great number of cases, that the normal current in any section is always in one direction and a fault causes a reversal of the current in the faulty section but in no other part of the system. Both, sensitivity and selectivity may, therefore, be obtained by using a directional element, which prevents the protective device from operating with normal direction of current, and permits a relatively low setting for current in the direction opposite to normal. In the practical application of this principle, there are two difficulties to be surpassed. The first is, that direction of current in the A. C. systems means the reactor relationships between voltage and current. Hence, to apply the reverse current principle, potential must be introduced as the base of reference. It has been suggested to use as a reference, a current whose direction is fixed, such as the fault current in a ground neutral. This scheme is not used very extensively; potential is ordinarily the standard reference. Since, under abnormal conditions, the voltage may fall to a very low value, it is necessary to make the directional element very sensitive. The second disadvantage arises from the fact that transients may occur, resulting in a momentary reversal of power, which it is desired to have the relay classified as normal. To overcome this disadvantage, it is usual to combine a very sensitive instantaneous direction element capable of operating at very low values of voltage with an over-current element having time-characteristics. Such a protective combination is very useful.

567. Comparison of Induction and plunger-type of Relay :—The plunger-type of relay, although widely used for simple applications, such as, the protection of meters, is not adopted to the accurate work required in automatically sectionalising distribution net-works. The main difficulty with these is that, their parts are easily loosened due to vibration and they fail to operate at the critical time. As a matter of course, the force on the plunger increases as the square of the current, with the result, that the force reaches enormous values when heavy short-circuits occur, and thus, they are seriously damaged resulting in their inefficiency at times of small short-circuits.

The plunger-type of relays, which depend on a bellow for their time-limit is unsatisfactory, because an extreme short-circuit compresses the air in the bellows till contact is made, and then at zero point in the current wave ; when the force on the plunger is released the air in the bellows expands and opens the circuit This chattering not only causes the contacts to be badly damaged by the arcing but delays the opening of the circuit-breakers. The definite time relay is usually so disigned that when the core is lifted, it compresses a spring which in turn acts upon the bellows. After the core has been lifted, the current required to hold it in that position is much less than that required to lift it, with the result that the relay will not rest until the overload has decreased to a current much smaller than the tripping value.

The plunger-type relay, having an oil-fitted dash-pot as its time-limit device, cannot be used for automatic sectionalising because of the great change in the viscosity due to changes in temperature. It is possible, that an automatic sectionalising scheme could be arranged in which case, the bellows-type relay might be sufficiently accurate but such accuracy could not be obtained except at considerable expense. In order to adjust relays of this type, it is necessary to disconnect them from the circuit and connect them to a test circuit which in many cases is not easy to obtain. Such calibrations must be made by a skilled tester and the process repeated for a change in the time-limit.

The best feature of the induction type of overload relay is its remarkable accuracy and permanence of calibration. The use of permanent magnets as time-limit device, prevents overswinging and chattering of the contacts, and the construction is such that, the relay will instantly cease its movements when the overload disappears. There is no possibility of mechanical injury due to excessive currents when the torque compensator is used, because the saturation of iron prevents the mechanical forces from increasing beyond certain limits.

The current and time adjustments of the induction inverse time element relays are plainly and accurately marked and any desired change can be made at a moment's notice. This feature is much appreciated by the operator who is responsible for the successful operations of the automatic sectionalising devices on his system. He can personally check the setting of every relay and thus be sure that no incorrect operations will result due to the carelessness or incompetence of an assistant operator.

Trouble of relays.

Symptom.	Trouble.	Cause	Remedy.
1. Circuit-breaker does not open when load reaches a point considerably in excess to normal relay setting.	*a* Timing element defective.	*a.* Air vents closed too tightly.	*a* Open air vents slightly; oil the bellows with neat's foot oil.
	b. Plunger of plunger-type jammed.	*b.* Heat from relay coil buckling the case, in which the plunger moves, preventing it from moving.	*b.* Replace coil with a new one.
	c. Disc of induction-type rubbing or out of place.	*c.* Disc-jewels broken or out of place due to vibration.	*c.* Renew jewels.
	d. Grease or dirt on relay contacts.	*d.* Relay cover not dust-proof.	*d* Remove all dust and grease.

Symptom.	Trouble.	Cause.	Remedy.
2. Circuit opens immediately on over-load, although a certain time delay was given The relay when last set and inspected	*a.* Air escapes too freely from bellows of plunger-type.	*a.* (i) Hole in bellows, (ii) air vent open.	*a.* (i) Replace or patch bellows, (ii) Close air vents.
	b. Magnet out of adjustment in an induction-type.	*b.* Adjusting mechanism loose or broken by vibration.	*b.* Read just position of magnets and tighten all screws.
3. Overload relay does not function although the relay itself is in perfect condition.	*a.* Contact circuit broken	*a.* Accident or carelessness.	*a.* Repair.
	b Circuit between relay and current transformers opens.	*b.* Same.	*b.* Same
	c. Battery out of commission on D. C. trip or circuit closing relay.	*c.* Dry cells or storage battery not inspected, re-newed or recharged often enough.	*c.* Renew dry cells, recharge storage battery.
	d. Auxiliary or pallet switch does not open when breaker is closed	*d.* Faulty switch mechanism.	*d.* Repair mechanical defects.

Symptom.	Trouble.	Cause.	Remedy.
4. Circuit breaks	*a*. Contacts on circuit closing auxiliary switch do not make contact.	*a*. Contacts bent or burnt or contact toggle too tight.	*a*. Repair or replace contacts; and loosen oil toggles.
	b. Open circuit in closing coil or circuit	*b*. Due to short-circuit or mechanical defect.	*b*. Repair circuit or coil.
	c. Fuse on closing coil blown.	*c*. Short-circuit in coil or circuit.	*c*. Instal new coil and replace fuse.
5. Circuit-breaker will not open on overload, where two or more are electrically interlocked.	Contacts on circuit opening auxiliary switch do not make contact.	Contacts bent or burnt or contacts toggle too tight.	Repair and replace contacts or loosen the oil toggle.
6. Circuit-breaker opens when underloaded and when provided with under-voltage coil and none of the foregoing defects are apparent.	Circuit to voltage coil opens.	Blown fuse or break in wiring.	Repair break or replace fuse

568. The protection chiefly required in the station is mainly divided into three main items :—

(1) Protection of the Alternators

(2) Protection of the Transformers.

(3) Protection of the Feeders and Transmission Lines.

The protection is achieved by means of various types of relays whose action, principle and the design point are given briefly. Each relay, functioning and attending immediately any unforeseen dangers, relieves the supply machinery of any fatality.

PROTECTION OF ALTERNATORS.

The chief abnormal conditions under which it is necessary to remove alternators from service are as follows :—

(1) Insulation faults between phases or between phase and earth.

(2) Insulation faults between parts of the one phase.

(3) Failure of field.

(4) Failure of prime-mover.

(5) Over-loading

(6) Motoring.

In some large power-stations, the engineers, preferring to rely upon the alertness of their operators, have no automatic protection on the generators. It is certainly questionable whether any automatic protection is necessary against faults (3) and (4). If, however, it be decided that some automatic protection is necessary, to guard against failing field only, a relay with a time element can be installed, which will open the main switch when a drop in excitation voltage occurs. But if protection is also required against motoring or a failure of the prime-mover, a reverse power relay must be resorted to. The latter, however, must be provided with some time element feature to prevent it from disturbing the continuity of supply by isolating its machine at times when momentary reversals occur.

The break-down of insulation in a generator circuit, is a more serious matter, as, under these conditions, not only is the supply jeopardised, but abnormal stress is put upon the conductors of the sound machines for several periods. Mr. Miles Walker has drawn attention to the fact, that a machine running on a dead short at its terminals may momentarily generate 20 or 30 times its full load current, and from this some idea can be gathered as to the amount of current which would be fed into a generator fault, when in a large power-station with several machines in parallel.

The ideal generator protection would isolate the faulty machine within a fraction of a cycle without interference with the other machines. The nearest approach to this ideal, is obtained by the balance system of protection. The fuses in parallel with the relay may be used for overload protection, The usefulness, however, of the fuse in this instance, is limited, as under ordinary circumstances, it would need to be set very high and could not be considered a sure means of operating in the event of a bus bar fault occurring; its chief use is that it permits of a light overload setting on special occasions, such as when a separate machine is running on a test.

The reactance of alternator windings is generally such that they can withstand a severe external fault such as a phase short-circuit without damage. Hence, there is little value in protecting them against external faults. If, overload protection is employed, the relays must be set very high for two reasons ; (1) to allow selective opening of feeder breakers upon a fault in the feeder ; (2) to avoid being tripped by the momentarily large circulating currents that may flow during synchronizing Hence, alternator protection has resolved itself into protection against internal faults only, at least for large central station generators. Protection against internal faults is ordinarily restricted to the armature circuit because of the low voltage of the field windinsg and the rarity of trouble therein.

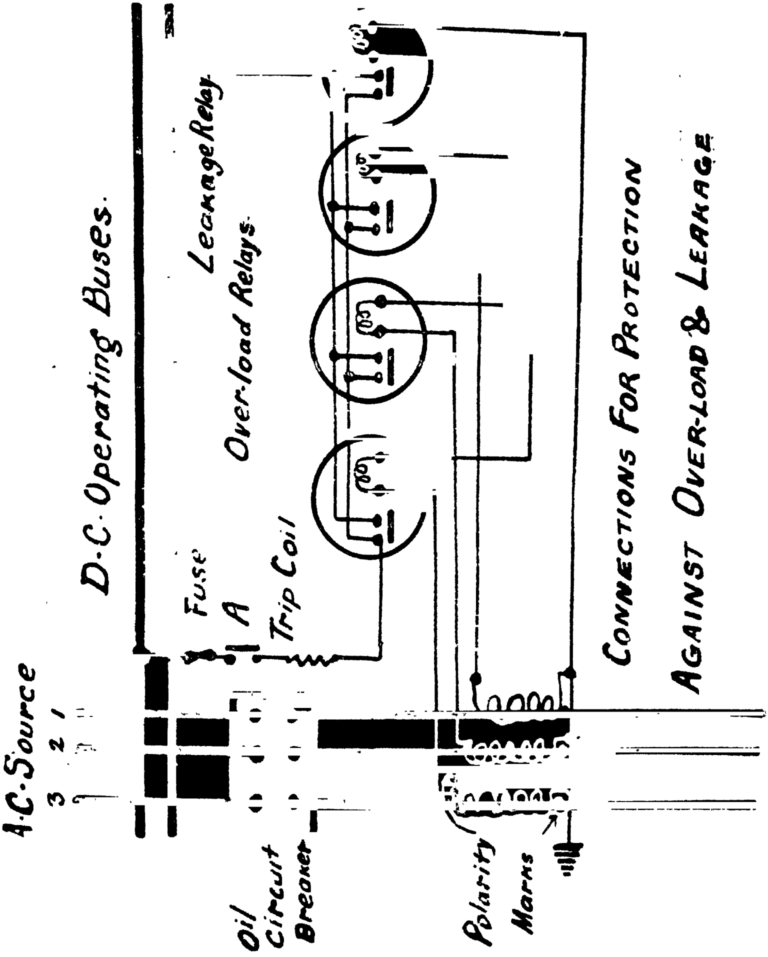
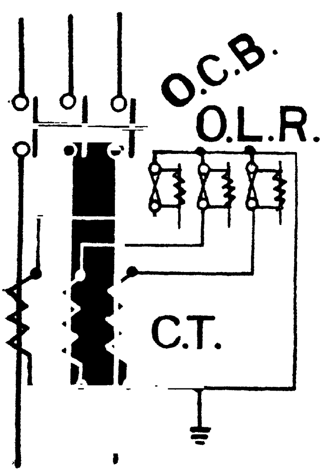


Fig. 10'10

569. Over-load Protection:—This form of protection will provide against most of the abnormal conditions to which alternators are subject, but it is very

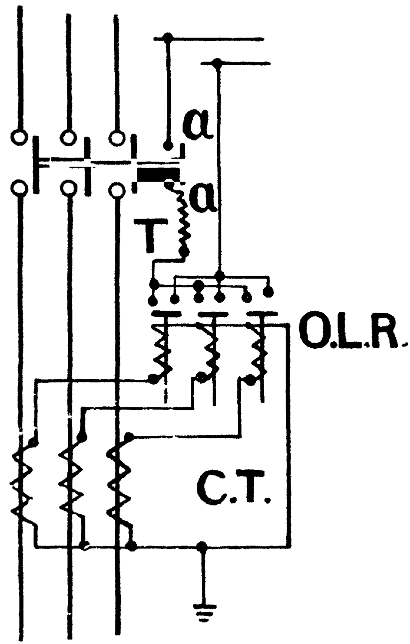
insensitive, and it is also very defective on operation under service conditions where a number of alternators normally run in parallel. In such a case, if an overload occurs on the system, the most heavily loaded alternator will first be disconnected from the bus-bars, leaving the overload to be shared by the other alternators, which will be disconnected one by one until the system is entirely shut down.

This feature is so objectionable that the use of overload protection has been almost entirely abandoned



Overload local relay, with fuse time element.

Fig 10·11

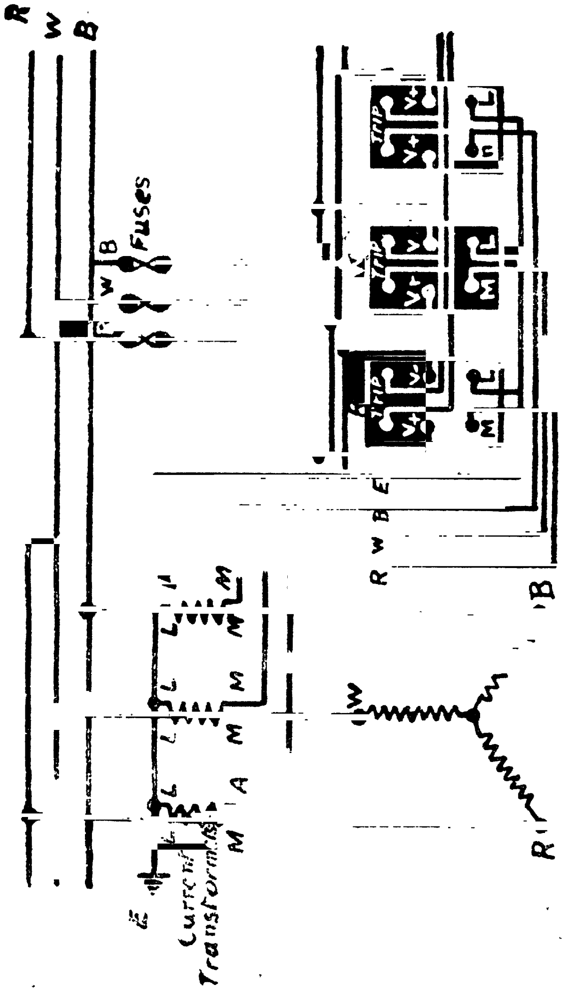


Overload relay without fuse time element

Fig 10·12

Fuse is generally used at the inverse time element for the plunger type of relay. The rating of fuses is

less definite and hence they are not generally employed



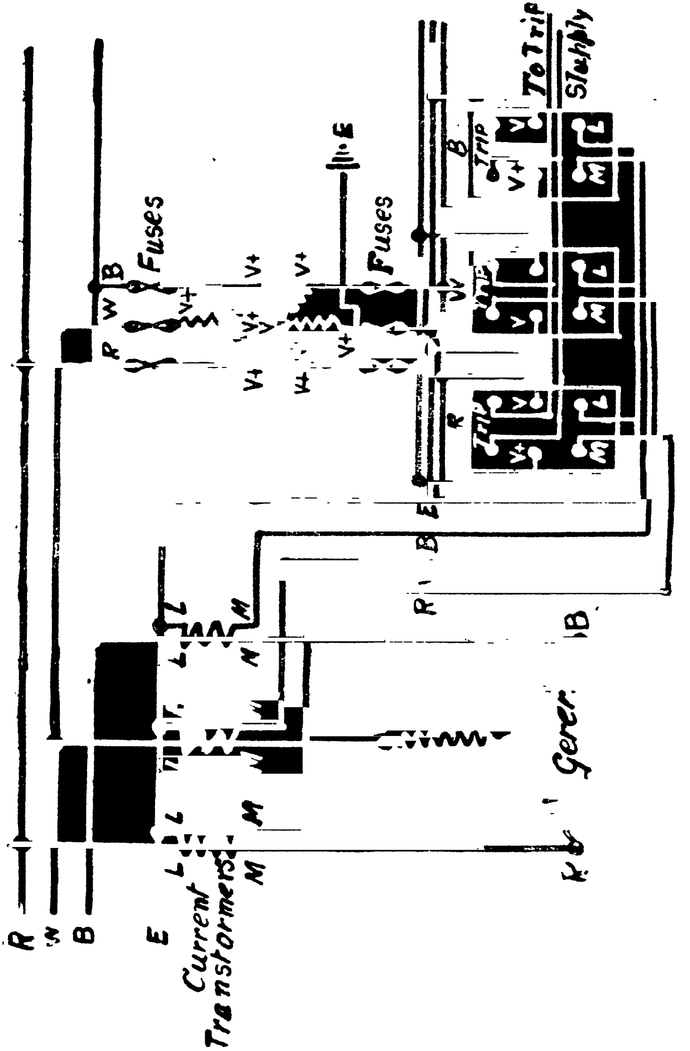
Reverse power relay connections for voltages below 500 volts.

Fig. 10·13

in important circuits Owing to the uncertainty regarding the condition of wire and its cooling facilities, it is not possible to utilize this time element to the same degree as with induction type contact-making relays. But the induction type is more costly. Plunger type relay with fuse time element is therefore generally used for the over-current protection of alternator and transformer.

570. Reverse Protection :—This form of protection will protect against failure of field, failure of prime-mover or motoring and will also protect against insulation faults when they attain to considerable magnitude. The relay used, has a movement of the same type as that of an induction indicating watt-meter, the disc being prevented by means of a stop on its periphery from rotating, when the power in the circuit is in the normal direction. Rotation in the reverse direction is controlled by means of a small weight, and an inverse relay action may be obtained, if desired.

Reverse power relays are used to prevent the absorption of power by the alternator or transformer from the bus-bars. The reverse power relay may either be a dynamo-meter type or induction type watt-hour meter. Generally the induction type is used. The action of the relay is such that when power is reversed due to either decrease in voltage or any other fault in the machine, the disc of relay will rotate in reverse direction and close the auxiliary contacts which actuate the tripping coil of the oil-circuit-breaker. Modern watt-meter type reverse power relay can be relied upon to operate on forward power under any circumstances, and to operate on reverse power at a percentage down to 10% of normal voltage. The induction type of relay is provided with a time element which does not allow the closing of the contacts for momentary reversal of power. For complete protection, two relays are needed for 3-phase system with insulated neutral, and three relays if the neutral is earthed. When leakage protective relay is employed, reverse power relay, in one of the lines only, is sufficient to obtain discriminative



Reverse power relay connections for voltages above 500 volts.
Fig. 10'14

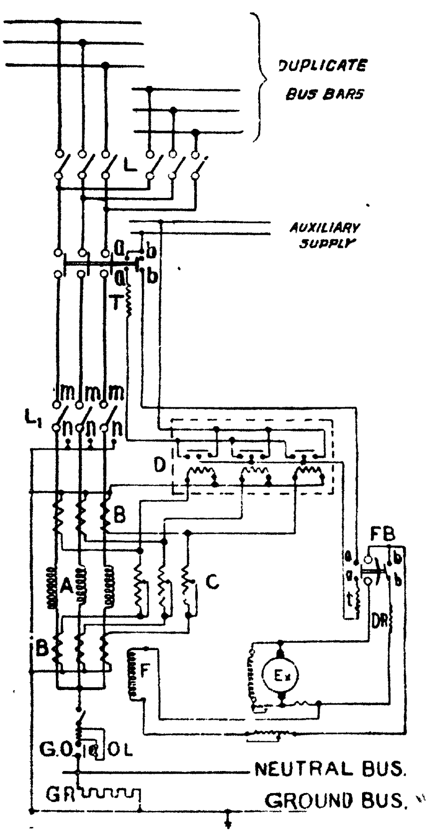
protection. The relay can be set to operate either instantaneously or with any maximum time limit upto 15 seconds. The time-limit will vary with the magnitude of reverse power which represents a maximum time-limit of 15 seconds.

571. Merz-Price Protection.—There are two types of Merz-Price Protection :—

(1) The circulating current method, and

(2) The opposing voltage method.

The circulating current method is generally adopted for the protection of alternators and transformers, whereas, the opposing voltage method is usually adopted for the protection of feeders. The superiority of the first over the second, lies chiefly in that it is possible to obtain more perfect balance between current transformers as regards their current ratios than as regards their terminal voltage with varying primary currents. The disadvantage of the circulating current method is that, current always circulates through the secondary of the current transformer.



Merz-Price circulating current generator protection.

Fig. 10·15

A—Winding of the 3-phase alternator with earthed neutral.

G.O—Neutral grounding oil-circuit-breaker provided with an overload relay having fuse as the time-limit element.

GR—Earth resistance.

Ex—Exciter of the alternator.

F—Field of the alternator.

L. L—Isolating link of which *L* is provided with double through arrangement. *L*, when makes contact with *m*, connects *A* to the bus bars, and when makes contact with *n*, short-circuits all the three-phases and connects them to earth in order to discharge any residual charge in the alternator.

B. B—The current transformers of which the secondaries are connected in series by pilot wires.

KKK—Equipotential points on the pilot wires. The connections are taken to the relay *D* from these equipotential points.

CCC—Adjustable resistances added in series with the pilot wires and enable the equipotential points to be located at one end instead of at middle, the point of the pilot wires which simplify the task of locating equipotential points.

Under normal working conditions when no fault exists in the insulation of the alternator windings, the same current flows through the primaries of the two current transformers, and consequently, the secondary windings of the current transformers contribute equally towards the current which flows through the pilot wires. At that time, no current will flow through the relay coils. When a fault occurs in the insulation of any one of the alternator windings, which allows current to flow to earth, the current in the primaries of the current transformers *BB* will no longer be equal, the current thereby being forced through the windings of the relay.

O—Main oil-circuit-breaker.

T—Trip coil.

aa—Contact closes when circuit closes.

bb—Contact closes when circuit opens.

FB—Field circuit-breaker.

t—Trip coil of the field circuit-breaker.

DR—Field discharge resistance.

When current flows through the relay coil, the relay contact points are closed which excites the trip coil *T* of the main oil-circuit-breaker and opens the oil-circuit-breaker. As soon as the oil-circuit-breaker is opened, the auxiliary contact points *bb* of the O.C.B. are closed and thereby the trip coil *t* of the field circuit-breaker is excited and stops the flow of current to the field of the alternator by opening the field circuit-breaker. This does not allow any further flow of leakage current.

The relay can stop the steam supply by closing the steam valve, or closing the gates for water turbine, or stop the fuel supply in the case of internal combustion engines, if the valves are electrically controlled.

572. Self-Balancing Protection:—The connection from the contact points of the relay is exactly similar to that of the Merz-Price type.

One of the chief advantages of the self balancing system, over the Merz-Price System lies in the fact, that under normal conditions no current flows in the secondary circuits of the transformers. Because of this, the risk of incorrect operation due to accidental open-circuiting or short-circuiting of the connecting wires, is minimised.

Self-balancing protection is more sensitive than the Merz-Price protection, and there is no risk of operating of protection due to unbalance between current transformers. Another advantage is that, three current transformers are only required for three-phase machines, as against six for Merz-Price protection.

Neither Merz-Price system nor self-balancing system affords protection against faults between turns of the same phase. Self-balancing gear will, however, protect a greater portion of the machine windings because of its greater sensitivity.

Circulating current system cannot give stable protection under severe emergency faults occurring in the transmission of distribution line along with the fault of the phase winding.

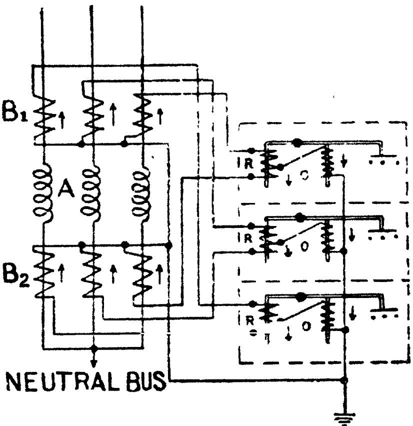
Self-balancing system gives stability under severe emergency conditions, and lowest possible fault setting may be obtained.

573. The Simple Differential Protection for Generators:—This is the most common form of generator protection. It is very simple and effective under most conditions of trouble. It has some limitations such as to protect against short-circuited turns and open circuits, also when a high ground resistance is used ; it does not operate on a ground until a short has developed, unless given a very sensitive setting. Such sensitive settings are sometimes difficult to obtain, since current transformers would be required to have identical characteristics in order to prevent a certain amount of unbalance, in case of heavy external short-circuits. Even slight manufacturing variations in duplicate current transformers cause enough unbalance to actuate the relays unless the secondary circuit burdens are kept low, so that the current transformer cores do not saturate. (See for instance in Merz-Price Relay).

Principle of Operations:—The leads of the machine to be protected are brought out and current transformers of the suitable range are introduced at both ends of the windings in each of the phases. The secondaries of the current transformers of each phase are connected in series and an instantaneous circuit closing relay is connected in parallel with each pair of current transformers. With the normal operation of the machine, the same amount of current flows in both No. I and No II current transformers and, therefore, no current flows through the coil of the relay. But in case of an internal short-circuit between phases or an internal ground, an unbalanced condition is set up. A greater amount of current flows in one transformer than in the other. Therefore, the unbalanced secondary current passes through the relay, and if this current exceeds the minimum current value for which the relay is set, the relay operates instantaneously

tripping the oil-circuit-breaker. A very sensitive action of the relay is made possible in the *differential protection* due to the fact that the currents are well-balanced under normal conditions, and hence, any slight abnormality of short-circuit is bound to upset the balance and put the relay into immediate operation.

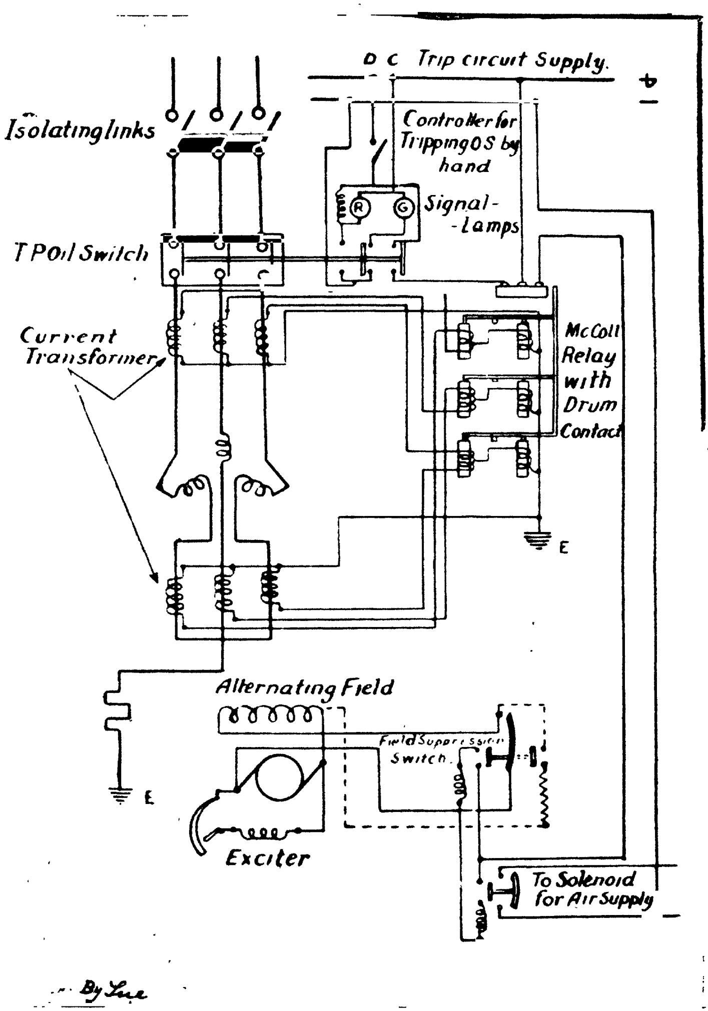
574. McColl Mechanical Biased Beam Relay :— The principle is the same as that of the Merz-Price circulating current system. The current circulates through the secondaries of the current transformers and the restraining coil R of the beam relay. A tapping from the middle of the coil R is taken and connected to the operating coil O of the beam relay. Under normal condition, when there is no fault, no current flows through the operating coil O of the relay.



McColl Mechanical Biased Beam Relay for Generators.
Fig. 10·16

On the occurrence of fault due to leakage or any other cause, the flow of current in the secondary of the current transformer B_2 will increase, and thereby operating coil is excited and operates the relay. If 12% fault setting is wanted, the operating coil must have 100/12 times of the turns of that of the restraining coil. Then if the leakage current exceeds 12% of the normal full load, the operating coil will pull the plunger down and close the contact point thus exciting the trip coil.

If the current is reversed *i.e.* flows towards the machine from the bus bars, the operating coil will carry the sum of the currents in the transformers on both sides of the winding. The current divides and flows through each half of the restraining coil in opposite directions. With this arrangement there is a definite guarantee of stability.



Complete Connection of Biased Differential Protection of Alternators.
Fig. 10·17.

Provision for automatically opening of field circuit-breaker of the alternator on the opening of its oil-circuit-breaker has been made. The chief reason for opening the field circuit is that in case of short-circuited coils, a current would be induced in the coils, as long as there is excitation on the machine even though the oil-circuit-breaker has been opened. The arrangement by which the oil-circuit-breaker connecting the alternator to the buses is made to open before the field circuit is interrupted, is accomplished by having a circuit-closing auxiliary switch on the oil-circuit-breaker.

The preference to open the oil-circuit-breaker before the field switch and not *vice-versa* is mainly due to the following items:—

When the field circuit is opened after the oil-circuit-breaker, there is less liability of danger to the field circuit, due to the high voltage, which will be induced in the field by the armature if the field circuit were to be opened when heavy currents are passing through the armature endangering the insulation.

The opening of the field switch after the oil-circuit-breaker has been opened, also reduces the possibility of the alternator falling out of step with the remaining of the system.

If the field switch were to be opened after the line circuit-breaker, the possibility of trouble in these respects is greatly reduced, though not entirely overcome.

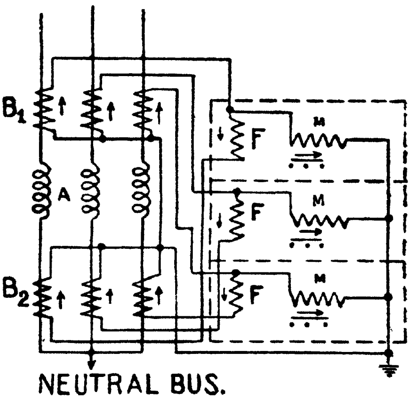
This arrangement requires either solenoid operation of the field switch or manually operated field switch equipped with a shunt trip coil.

In the case of solenoid operated switches, this auxiliary switch forms a part of the standard equipment, whereas, in the manually operated field switches, an auxiliary switch is provided to open the shunt trip coil circuit when the breakers open.

The instruments or meters, connected to the same current transformers, are connected in the secondaries of the two sets of current transformers in such a way as to give balanced secondary volt ampere leading as closely as possible.

The degree of sensitivity for which the relay may be adjusted, depends on the similarity of the current transformers. Opinions differ as to the best settings. Differential current settings ranging from 5 % to 100% of full load current have been used satisfactorily in various applications. No definite rule can be set down in this respect, but it is recommended that the settings should be made as low as possible under local conditions; satisfactory operations can be obtained over a wide range of settings but the lowest possible setting has the advantage that the amount of damage done to the machine would be a minimum. This scheme is flexible in its application and can be applied to machines of any size either star or delta-connected, provided both ends of each phase winding can be brought out and connected through current transformers. This scheme, as applied to delta-connected generator, includes protection of the generator leads as well as the windings. All the current transformers should have the same ratio. Simplification is possible if generator lead protection is not required. In that case only six current transformers are required and each phase winding is protected as in the case of a star-connected generator.

575. Biased Reactive Relay: – The principle is the same as that of McColl beam relay. The relay has got two elements--F, the fixed coil and M the moving coil. When the current flows through each of the coils, the moving coil moves according to the dynamometer type of instruments. On this system under normal conditions the current out-put of transformer B_1 is greater than that of the



Biased Reactive Relay for Generators.

Fig. 10·18

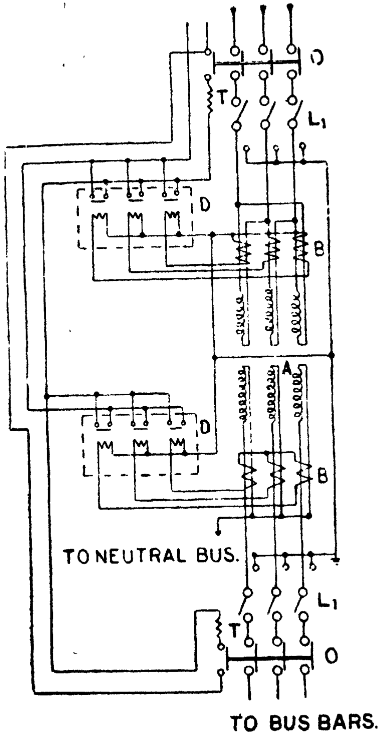
transformer B_2 and therefore the difference of the two currents flows through the moving coil M. The fixed coil F carries the out-put of the transformers B_2. The arrows indicate the direction of the flow of current under normal conditions. At that time the moving coil turns to the opposite direction of the contact points. When a fault occurs in the windings of the alternator, the current flowing through the primary of the transformer B_2 increases, thereby increasing the current out-put of the secondary which decreases the current flowing through the moving coil.

The current through the moving coil is reversed with further increase of the fault current which movement closes the contact points.

If the generator has to contribute abnormal current, due to fault outside the transformer B_1, the small local current which gives normal bias will increase and add to the stability of the relay. It is advantageous to run with a small percentage of bias at normal loads, the percentage being automatically increased with severe emergency conditions. This may be increased by designing the transformers B_2 such that it becomes saturated at lower value of abnormal current than the transformers B_1. The effect is increased percentage bias at emergency load *i. e.* short-circuits.

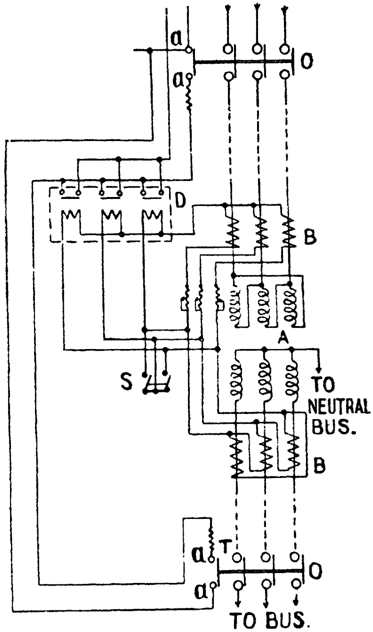
PROTECTION OF TRANSFORMERS.

576. Self-Balancing Protection :—This type of protection will provide against short-circuits in a transformer between phase and earth. It cannot protect against faults between turns of the same phase. Since the balance is obtained between the currents entering and leaving each individual phase winding, and not between the current entering on the primary side and that leaving on the secondary side of the transformer, as in the case of Merz-Price Protection, there is no danger of operation due to relative difference between primary and secondary currents, which difference may be considerable at the moment of switching in.



Self-balancing Protection for Transformers.

Fig, 10'19



Merz-Price Protection for Transformers.

Fig. 10'20

577. Merz-Price Protection:—This form of protection will provide against faults in the transformer between phases or between phases and earth. It will also protect against faults between turns of the same winding if such faults are sufficiently extensive to alter considerably the ratio of transformation.

The principle on which the gear operates is that of comparing the primary and the secondary currents of the

transformer which is to be protected, the means adopted being precisely similar to those which have been already described in connection with the alternator protection, with the important difference that the ratio of the current transformers used on the primary and secondary sides varies proportionately in the ratio of transformation of the transformer which is protected.

Proper balance in the currents cannot be obtained in this type of protection at the time of switching the transformer in circuit. There will be too much of difference of the primary and the secondary current of the transformer, on account of which the relay operates and does not allow the transformer to put into service. To overcome this difficulty the relay coils are short-circuited by the switch at the time of switching in the transformer.

When delta-star transformer is protected, it is necessary to connect the current transformers on the delta side star and *vice versa* to obtain correct phase relations. In order to obtain balance, the current transformers should be designed in such a way that which are connected in star should give a normal secondary current equal to $\sqrt{3}$ times the normal secondary current of the current transformers which are connected in delta.

Merz-Price protection is less sensitive than the self-balancing protection but it is convenient on application.

In the case of alternator protection, so long as the insulation of the winding protected is not faulty, the current passing through each pair of current transformers must be the same. In a transformer, a certain amount of current is taken in the primary side which is absorbed by losses in the transformer, and which has no counter-part on the secondary side. Under ordinary conditions, whether the transformer is on load or not, the only effect that this current has, on the protective gear is, to limit the sensitivity which may be obtained. At the moment of switching in, however, a very heavy current may be taken momentarily to magnetise the transformer core, the value of the current varying with the direction of any residual magnetism

in the core and with the polarity and voltage of supply at the moment of switching in.

The effect of this current is frequently so considerable as to cause the operation of the protective relay immediately on switching in, and to render it practically impossible to put the transformer into service.

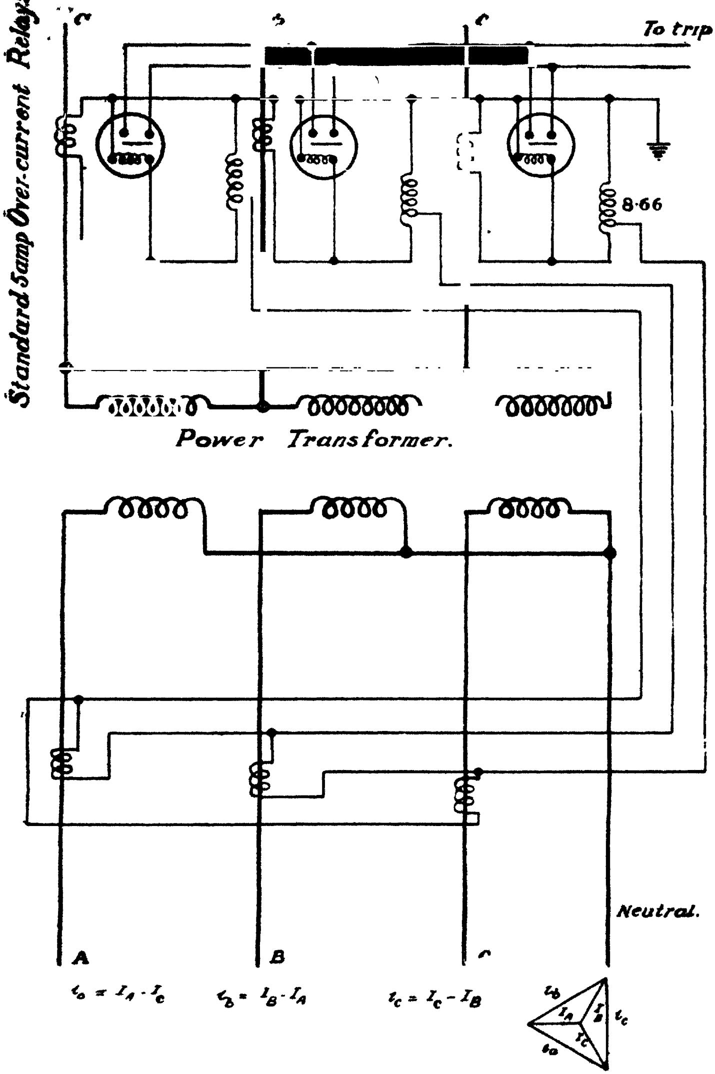
Various devices have been suggested and used in order to overcome this trouble, the chief of which are as follows :—

(*a*) Probably the most satisfactory arrangement is to employ controlling oil-switches which have charging resistances incorporated in their construction, which limit the value of charging current. Such charging resistances are very desirable in order to minimise any tendency towards surging at the moment of switching in a transformer with consequent high voltage on the end-turns of the transformer windings.

(*b*) If the oil-switches have no charging resistances it may be necessary to embody some device in the protective gear. The most satisfactory arrangement is to use a small double-pole switch. This switch should be closed at the moment of switching in and opened immediately afterwards, its effect being to render the protective gear inoperative by short-circuiting the relay coils. It is desirable that the switch should be mounted on the handle of the controlling oil-switch and should automatically return to the open position when the hand is removed from the oil-switch handle.

(*c*) The other alternative device which may be applied to protection is to provide a time-limit feature for the protective relays, either by means of fuses shunting the relay coils, or some other method. This arrangement cannot be considered entirely desirable, since a considerable amount of damage may be done to the apparatus protected in a very short space of time under fault conditions.

578. Differential Protection of Transformers :— Fig. 10·21 shows the differential protection of a delta-star connected 3-phase transformer bank. The current transformers on the primary side are connected star, while



Differential Protection of a Delta-Star 3-Phase Transformer Bank.

those on the secondary side are connected delta. The ratio of the current transformers on the two sides is so arranged that the currents on the primary and secondary side current transformers are equal and in phase. These are now connected to the overload relays shown, so that, the two currents oppose each other. When any unbalance in currents on the two sides takes place, the overload relay coils carry current and trip the circuit-breaker and thus disconnect the transformer from the supply. This scheme protects the transformer against (1) phase-to-phase short-circuits, (2) short-circuited turns, and (3) low resistance grounds.

This scheme does not protect against open-circuit of a high resistance ground.

579. Percentage Differential Transformer Protection :—Three winding transformers present difficult problems for the protection engineer. The special requirements of these transformers necessitated that any suitable scheme of protection in case of an internal fault, must receive the transformer from all three of its associated circuits simultaneously. In addition, an external fault on any one of the associated circuits must be cleared without putting the transformer out of service. Differential relays, operating on the phase difference between the currents, are particularly adopted to meet the requirements.

Occurrence of an internal fault in a three-phase power transformer requires the complete isolation of the transformer in the shortest possible time. In addition, the protection must carefully discriminate between internal and external faults such as those occurring on associated transmission lines. It would be desirable of course to have a protection sufficiently sensitive, so that it would function on the least possible fault, *e.g.*, one between adjacent turns. Among other factors which affect sensitivity, are possible false operation and economy of winding replacement. Assuming, that the protective relays would act instantaneously, even a turn to turn fault would damage instantaneously several turns or a section of the winding before the O. C. B. would open. A ground fault inside a transformer, *e.g.*, winding

and core, is becoming a remote probability with the improvement of transformer design. For the same reason, the faults between phases are also becoming serious, consequently, the problem is principally of faults between turns or parts of the same winding. Differential protection of 3-phase power transformers, operates on the vector difference of the currents flowing in and out of the transformer. This protection is theoretically free from the effects of external faults ; because, neglecting the exciting current, the vector difference between these currents is zero, except at the time of an internal fault. The practical application of this theory has been accomplished by connecting in parallel, the secondary windings of all the current transformers in each phase, provided their ratios are such as to compensate exactly for the different voltage ratios of the power transformer windings. In practice, such differences, as do exist, are easily compensated for by using auxiliary auto-transformer circuits for secondary. Unfortunately, current transformers do not maintain the same ratio characteristics upto many times their full load rating. This is aggravated by the current transformers generally being of different types with one set, *viz*, the bushing type. This difficulty is overcome by using the percentage differential principles.

Percentage differential characteristics are, in effect, an automatic means of raising the setting of the relay at the time of a fault. This automatic raising of voltage is obtained by having elements in the relay energised by through currents, *viz*., the current in each of the power transformer windings. These elements act to oppose the torque of the operating element, actuated by the "difference" current. By proportioning the number of turns in these windings, it is possible to secure relay operating characteristics having any percentage required. The relay provides a separate restraining torque from each of the three power transformer windings. The current values for the torque are so proportionate that the operating current is a certain percentage of the average of restraining current. In practice, this proportion is as high as 50% at times. A great advantage of this percentage characteristic is that, it can be used

on power transformers with voltage taps even where voltage taps are automatically adjusted to meet load conditions. Control springs for adjusting the minimum operating currents are provided on these relays and are similar to those formed on induction-type over-current relays. Minimum current settings are determined from the probable inrush of exciting current to the transformer. In general, this magnetising current is only of the order of 5°/o of full load current. But at the instant of energising, an inrush of transient magnetising current generally results. The peak of this current can be eight to eleven times the full-load current rating of the power transformer, and that this current may remain greater than the full-load value for a relatively long time, 30 to 60 cycles.

Relatively high current settings are therefore required to prevent relay operation during these magnetising transients. One plan is to use an additional relay to momentarily raise the differential relay setting to a higher value when the bank is first energised. This relay is operated from a potential transformer placed across any one of the power transformer winding inside of O. C. B. connections. While the bank is de-energised, the voltage relay operates after a predetermined time delay, disconnecting the parallel resister from the differential relay after the cessation of the magnetising transient.

580. Bye-pass Protector : —In order to protect the windings of a current transformer from severe transient voltage, it has been found necessary, either to provide means whereby the transients may pass by the transformer without building up high voltages between turns, or to heavily insulate the turns of the winding. As the heavily insulated turns require valuable space that will affect the accuracy of the transformer, it has been found preferable to use a bye-pass protector.

A non-inductive resistance, placed in parallel with the transformer as a shunt for the primary, has been found to give good protection. If, however, this resistance is so connected continuously, it would affect the

ratio and the phase angle as to seriously affect the accuracy of instruments and meters, although it would not jeopardise the operation of trip coils or relays. A more satisfactory method followed is, therefore, to have the shunt-circuit open during normal operation and closed only during disturbances. A vacuum gap in series with the shunt resistance accomplishes this. But the vacuum gap may fail if it is seriously overheated, and prevent the transformer from operating the secondary tripping devices without giving any external indication as a warning. The most satisfactory arrangement is to place a small air-gap in parallel with the transformer.

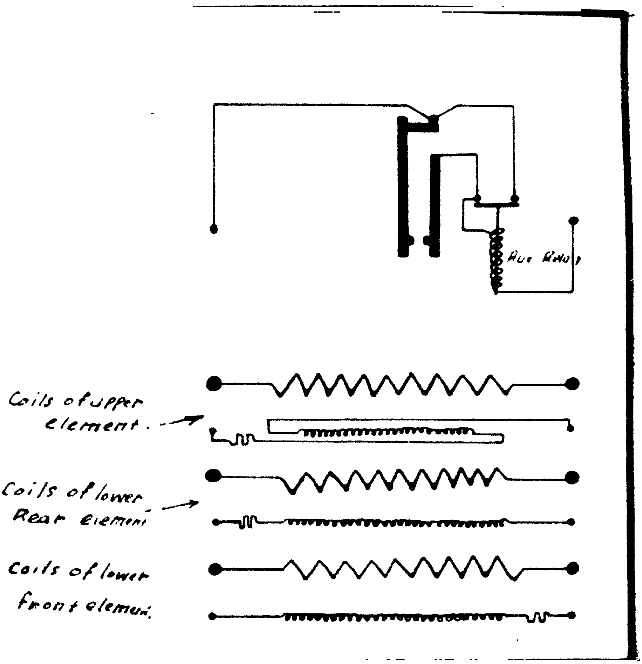
TRANSMISSION PROTECTION.

581. Induction Type Polyphase Power Directional Relays :—Use of these reverse power relays is felt at all transformer stations, where it is necessary to consider the safety of in-coming lines feeding the H. T. side of the transformers.

The power directional relays are constructed in polyphase units for switchboard mounting. They contain current and potential windings, and are suitable for use on alternating current circuits only. The current windings are designed for use in connection with the current transformers usually having the secondary normally rated at 5 amps., and the potential windings are for use with potential transformers having secondary ratings from 110 to 125 volts. Obviously, these relays can be used for circuits having current and voltage ratings that do not exceed those for which the windings are designed.

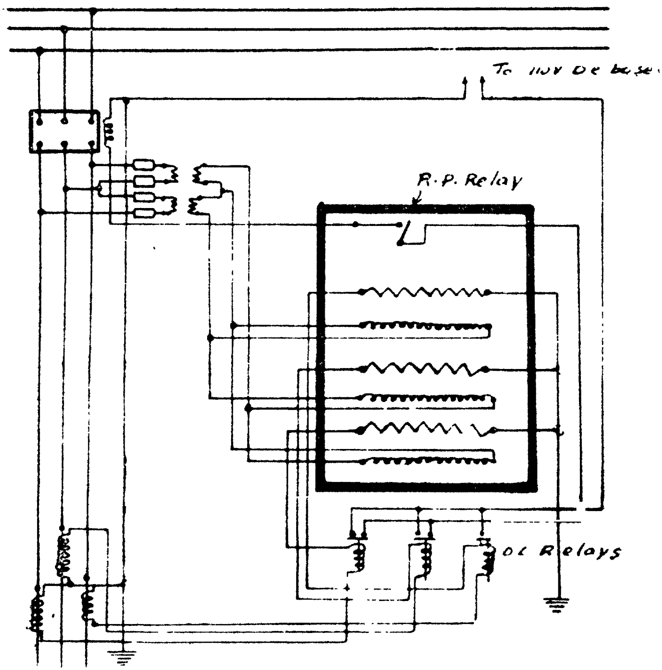
This relay is connected differentially to the current transformer secondaries. So long as balanced condition is maintained between the corresponding phases in the two lines, there will be no current in the differential or relay circuit. When a fault occurs, the vectorial unbalancing in the main circuits will be represented in the power directional relay coils, closing the contacts to the side for selecting the proper breaker. When one circuit-breaker is open, the balancing effect of the two lines no

To face page 880



Reverse Power Relay, Internal Connections.

Fig. 10·22A.



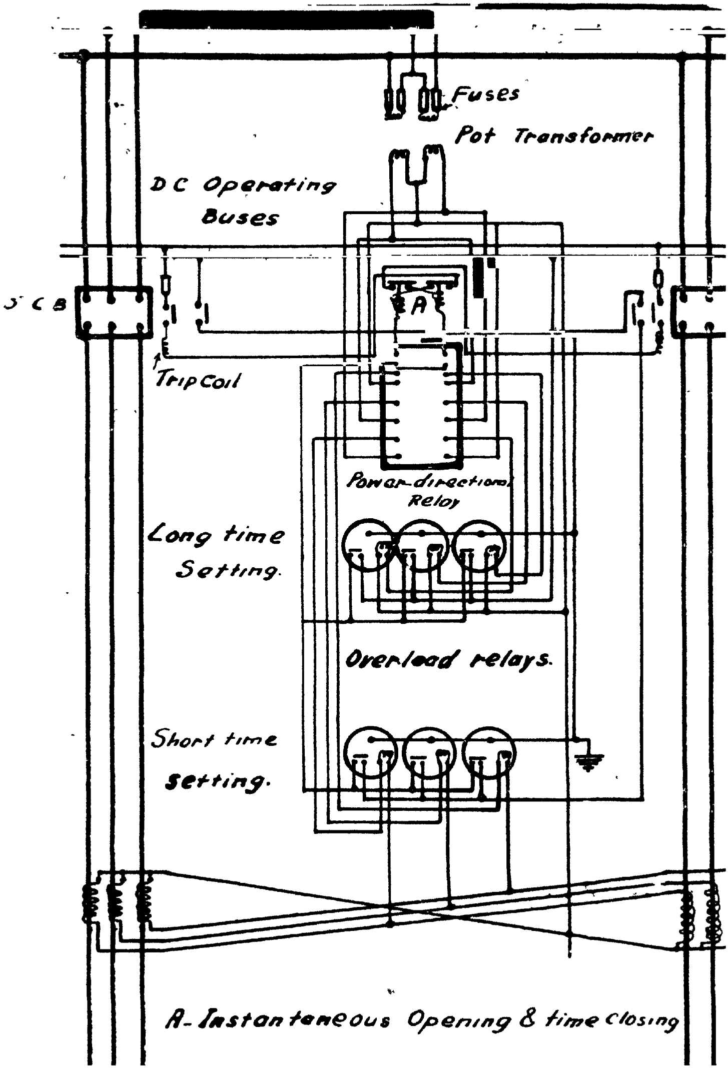
Reverse Power Relay, External Connections.
Fig. 10'22B

longer exists, therefore, it is necessary to introduce a time delay for further selective operation (for the other line existing in service). The opening of the circuit-breaker automatically opens its auxiliary switch. Therefore, in case of a fault with only one line in service, the trip circuit is established from the negative through the time over-current relay contacts to power directional relay contacts. If the power direction is from the bus to the line, the power directional relay contacts will be closed on that side as well as to trip the remaining side

The two sets of over-current relays are connected in series with the power directional relays across the differentially connected current transformer secondaries. The set of over-current relays with low time settings functions first in case of a fault in either of the in-coming lines with both lines in service. The circuit for the over-current relays with low time setting is connected through auxiliary switches on both breakers so that, after one breaker has opened, the tripping circuit of the remaining breaker must be completed through the contacts of the over-current relays with the larger time setting. This arrangement gives the desired longer time delay with one line in service.

Construction :—The relay consists of what is essentially the moving element of a polyphase induction watt-hour meter, that is, the relay contains two metal discs mounted on a vertical shaft supported on jewel bearings. Acting upon these discs to revolve them, are the three watt-hour meter elements, each element consisting of a current coil and a potential coil with a laminated soft iron core ; one such element used for each phase of a three phase circuit. One element is mounted to act upon the upper disc and the other upon the lower disc. When power flows in the normal direction, the discs tend to revolve to the right just like a watt-hour meter. Normally, when the direction of flow of power is reversed, the disc rotates the opposite way.

The relay is mounted in a cast iron dust-tight cover with glass slits to see the contacts and discs. The cover can be easily removed for any adjustment. A cast iron frame carries the connection and supports the whole

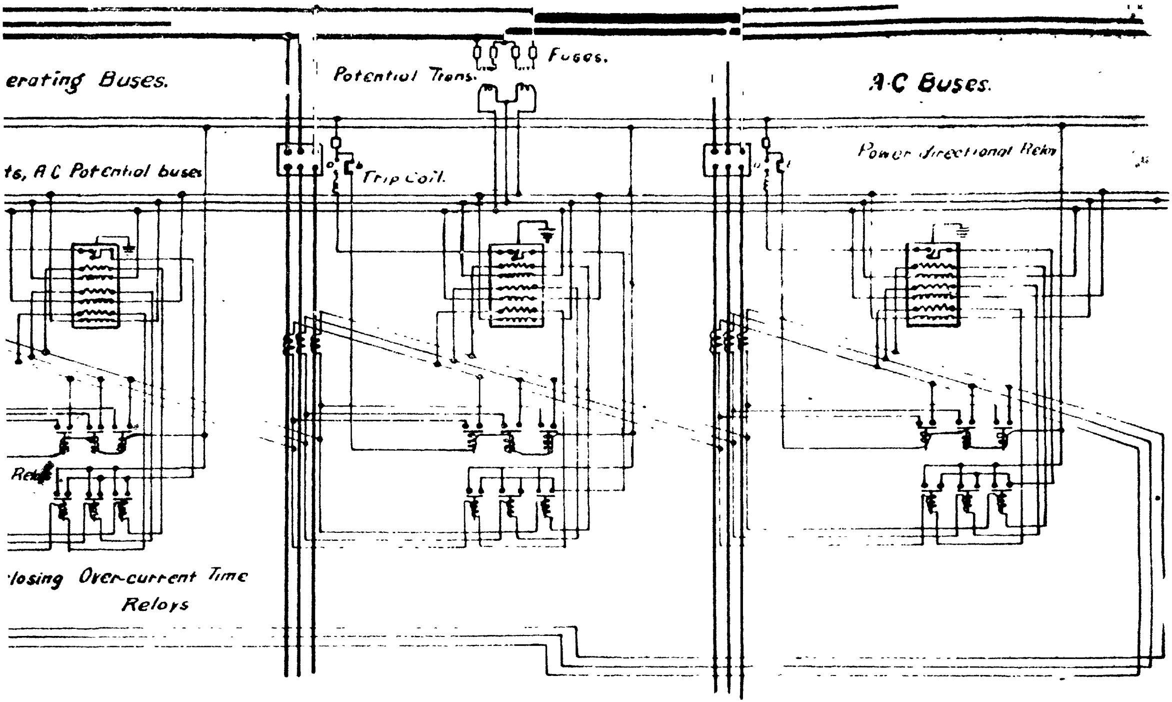

Fuses
Pot Transformer
DC Operating Buses
Trip Coil
A
Power-directional Relay
Long time Setting.
Overload relays.
Short time setting.
A- Instantaneous Opening & time closing

relay. The relay is equipped with two sets of contacts, one set closing with the right hand movement of the disc while the other closes with the left hand movement. The relay has, inside the case, an auxiliary relay, the coil of which is in series and the contacts of which are in parallel with the main contacts.

The function of this auxiliary relay is to "seal in" the main contacts and relieve thereby the current of the tripping circuit As soon as the main contacts close, current traverses the auxiliary relay coil causing it to function and close its contacts, the circuit thus remains closed until opened by some other means of an auxiliary switch on the oil-circuit-breaker.

Operation :—The operating principle of this relay is the same as that of the induction type watt-hour meter. As in a watt-hour meter the maximum torque is obtained when the current in the current coil and the potential applied to the potential coil are in phase. This means that the maximum torque is obtained when the current in the current coil and the current in the potential coil are in quadrature, since the potential coil is so highly inductive that its current lags approximately 90° behind its voltage. But in the case of these relays, resisters, in series with the potential coils, are provided so as to advance the current to be more nearly in phase with the potential of the circuit.

As serious faults result almost invariably in lagging currents, and experience having shown that an average value for such lag being 40° (0·76 P. F.), these relays are provided with resisters of proper value to give maximum torque for the P. F.



ctions for Protecting against Unbalanced Power in 3 or more Parallel 3-phase In-coming, Out-going or Tie Lines.

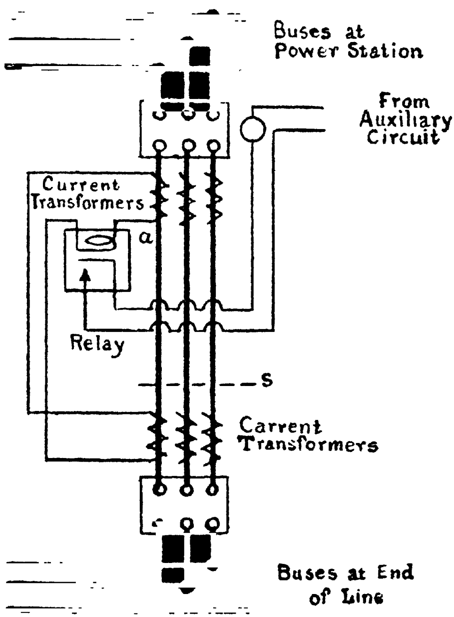
Fig. 1023

The relay can be used either as Over-Power relay or Power-Directional relay according as the contacts are allowed to close on over-power or reverse power. When the relay functions, the rotation of the shaft closes contact, and in series with this contact is the winding of the auxiliary relay. By exciting this winding the auxiliary relay is closed instantaneously. Fig. 10·22 shows the connections of the above type of relays for protecting two parallel 3-phase feeders against unbalancing of short duration. Also after disconnecting one line it protects the other line against reverse power that continues for a long time. The diagram is self explanatory.

Fig. 10·23 shows the external connections of the above type of relay for protection against unbalanced power in 3 or more parallel 3-phase in-coming feeders.

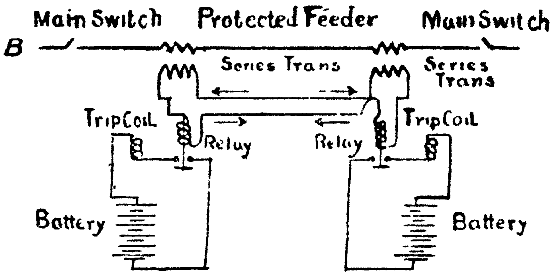
Minimum Operating Values :—These relays will operate and function when the lines to which they are connected are subjected to the following conditions :—

(1) Single phase short circuits, even where the voltages between the two lines, that are short-circuited, may fall to zero.



Merz-Price System for Protecting against Short-Circuits and Ground of Feeders.
Fig. 10·24

(2) **Balanced three phase short-circuits with 10 amp or higher secondary current and one per cent. of normal voltage.**



Merz-Price System of Protection of Feeders.

Fig. 10·25

582. The Merz-Price Protection for Feeders :—The principle upon which the system is based (same as in two previous cases) is the equality of the currents at the two ends of a normally balanced circuit. When the electrical continuity of a circuit is interrupted by a station transformer for the purpose of pressure alteration, the currents on the two sides are not equal in the mathematical sense, though at the same time by suitably designing the protective current transformers they may directly be compared. In a sound balanced system the currents, flowing in and out of the circuit, are the same or directly comparable neglecting losses. But if an earth fault or a fault between phases occurs, this equality is disturbed and the difference in the amounts or the ratios of entering or leaving currents is utilised for tripping the faulty apparatus out of circuit.

Protective current transformers are inserted in series on both H. T. and L. T. sides, and these are designed so that the secondary currents of the current transformer on the H. T. side are the same as the secondary currents of those on L. T. side.

The C. T. secondaries are arranged so that normal currents flow in the same direction round the circuit produced by the windings and the short pilot wire connections. Relays are connected to equipotential points between the current transformer secondaries, and with these so connected, there is no tendency for current to flow through the relays under normal conditions.

If, however, an earth fault or a fault between phase occurs in the main transformer or feeder, the currents in the C. T. secondaries will differ in magnitude or in phase or both, and the vectorial difference flows through the relay windings thereby operating the automatic oil-switches.

The relays are set to operate at a current value between 50 to 100 °/o higher than the minimum current at which they would operate.

583 Differential Protection :—The differential protection of parallel transmission lines has become very popular due to the following important features.

(1) It can be made very fast in operation.

(2) It is very selective since a fault produces an unbalance in the faulty section only.

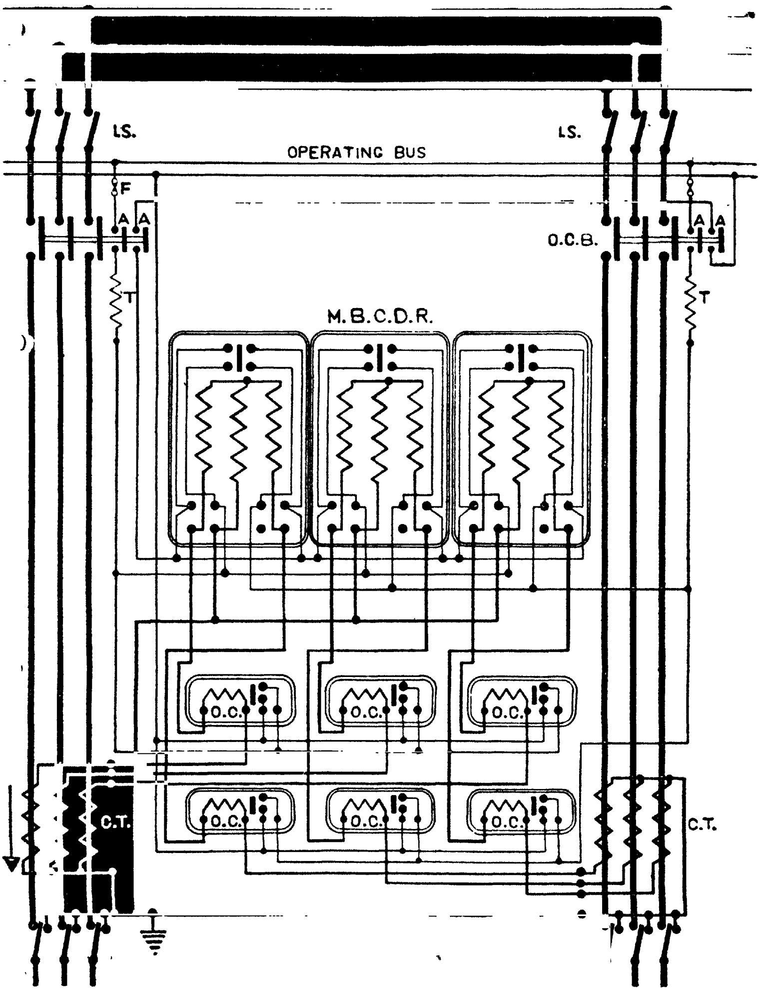
(3) The effect of low current setting is usually obtained in this scheme due to the characteristics of the relays or connections without the hazard of using low current taps on the phase relays. On ground differential relays, a low current tap may sefely be used, since current is normally zero

Special attention should be given to the following features in the application of this form of protection.

(1) It is obvious that the second line cannot be put into and taken out of service simultaneously at both ends. During this operation, an unbalance condition may exist due to load current flowing in one line only. Setting high enough to take care of this current must be used.

(2) Single line operation.—After one line has tripped or has been taken out of service, the remaining line must have some suitable protection

(3) Simultaneous faults on both balanced lines and



Mechanical Balanced Current Differential Relay for Parallel Feeder Protection.

Fig. 10·26

bus faults—such faults will, of course, produce no balance in the parallel lines and some form of protection should be provided to take care for them.

(4) The limitations imposed on system operation by the necessity of maintaining at all times an electrical parallel between the lines at the balance points, for instance, it may be desirable to sectionalise the bus to which parallel lines are connected. In this case the differential protection would have to be taken out of service and some form of single line protection to be used.

Fig. 10·26 shows the connection diagram for the protection of two parallel feeders using three above-mentioned relays and six over-current relays. As indicated by the diagram one restraining coil is excited from one current transformer line, and the other is similarly excited from the other line. The difference of these two currents flows through the operating coil.

The restraining coils, when excited, pull the plungers downwards thereby exert downward force at opposite ends of the moving contact mechanism and the operating coil excitation pushes the plunger rod upwards on the middle of this mechanism. The pair of contacts on the side, in which the larger restraining current is flowing, will be closed when the unbalanced current in the operating coil is sufficient to cause the operating coil plunger to raise the movable contacts.

When one set of contact closes, the faulty line is instantaneously tripped off. As soon as the faulty line is tripped off, the current through the restraining coil, excited from that line, will become zero and the total current through the other restraining coil will all flow through the operating coil. If this current is sufficient it will cause the relay to close its other set instantaneously. As it is not desirable for the second line to open unless it actually has a fault in it, two inverse time over-current relays are introduced in the circuit. These prevent the opening of the second breaker except on over-current. Over-current relays can be set to operate at any desired current, irrespective of the differential relay.

This type of relay may be used whenever the current in the two circuits is normally equal or in a definite ratio, and abnormal conditions can be remedied through closing of relay contacts. It is suitable for the following applications :—

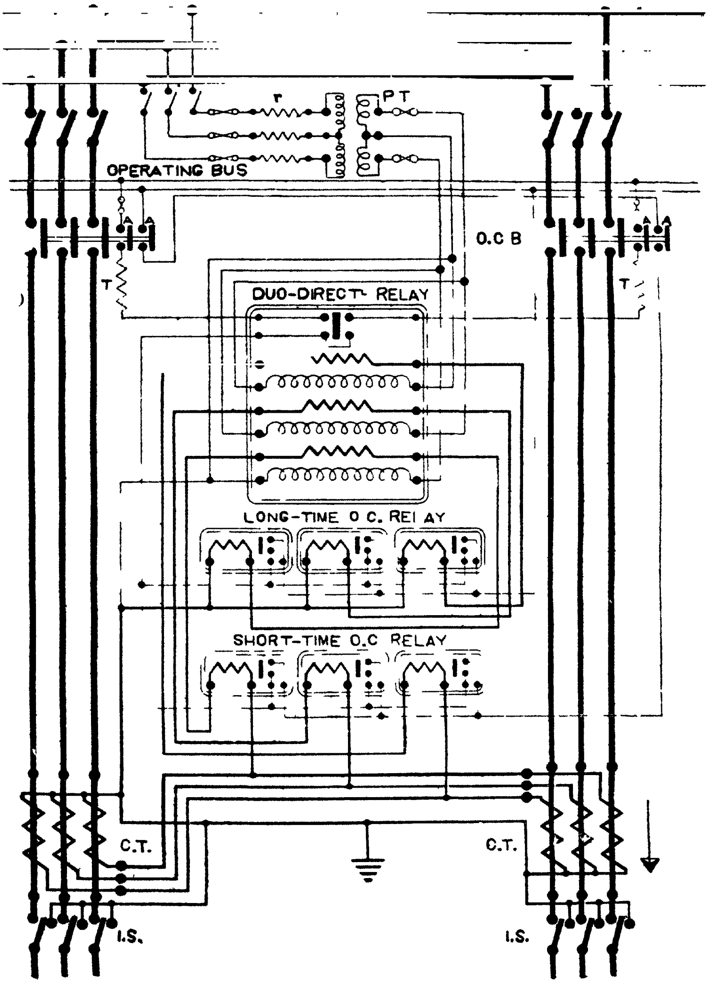
(1) At the out-going ends of two parallel lines that normally carry currents which are in a definite ratio one to the other.

(2) This relay is sometimes used at the in-coming ends of a pair of parallel transmission lines. This application is desirable only where the load is synchronous or where there is available, in case of short-circuits or grounds, a source of power of ample capacity to feed sufficient current, to feed back into the faulty feeder to operate the relay.

(3) It is applicable to short-circuit protection of power transformers. In this case the two restraining coils are connected one to a current transformer in the primary of the power transformer and the other to a current transformer in its secondary. The current transformers should be of such ratios that normally their secondary currents will be about equal.

584. Duo-directional relay :—Used in conjunction with short and long time over-current relays for differential protection of parallel feeders.

The duo-directional relay has got two discs only, mounted on vertical spindle, one of the discs is actuated by one and the other by two of the electro-magnetic elements. One set of contact points is closed by the rotation of the discs in one direction and the other set by the rotation in other direction when the previous set is opened. Considering the generating station end the current flowing through the faulty line is greater than that of the healthy one. The current and pressure elements of the directional relay are so connected that the contact points of the faulty line will only be closed and also the short time O. C. relay contact points will be closed thereby exciting the trip coil of the faulty line. The faulty line circuit-breaker will therefore be tripped at the generating station. If only the directional relays



Duo-Directional Relay used in conjunction with Short and Long time Over-current Relay for Differential Protection of Parallel Feeders.

Fig. 10·27

are connected at the in-coming end of the feeder, it will also trip the circuit-breaker at the sub-station end. When the faulty line circuit-breaker is opened, the short time O. C. relay contact points, though closed, will have no effect on the healthy feeder, as the series contact *A* of the faulty feeder is opened. As soon as the faulty feeder is tripped, the direction of the current in the directional relay is changed, thereby closing the contact point of the healthy feeder Now for the healthy feeder the long time O. C. relay will be operated if the current exceeds the setting value of the long time O. C. relay.

585. Network Protection Relay:—This relay is of the induction type and is for use on a low voltage A. C. Distribution network and is suitable for single-phase 2 or 3-wire; two-phase 3, 4 or 5-wire; or 3-phase 4-wire systems. It is used to control special network switch to obtain continuity of service, constant voltage on network, efficient operation of distribution, transformers and reverse current protection

Application:—This relay is a recent development and is used to simplify and solve many of the problems as encountered in low-voltage A. C. Distribution networks. In recent years, low voltage A. C. Dirtribution systems have been replacing the D. C. systems especially in large cities. Absolute continuity of service to customers is the most important requisite of any distribution system. This makes it necessary to have the system fed from several sources so that the failure of any one feeder will not interrupt service This gave rise to the distribution network which is an inter-connected low voltage system in which common mains, fed by a number of distribution transformers located at different points, are used to supply power to a number of customers. This relay is designed to—

(1) insure continuity of service on the network by serving to disconnect any of the feeders which develops a fault, thus preventing the tripping out of the other feeders by overload protection;

(2) insure a constant voltage on the network, as additional distribution transformers are connected to the

network automatically by the relay, when the load becomes such as causes a voltage drop of more than $\frac{1}{2}$ volt :

(3) insure the most economical working of the distribution transformers, as the transformers are only connected to the network when the ones already connected become overloaded.

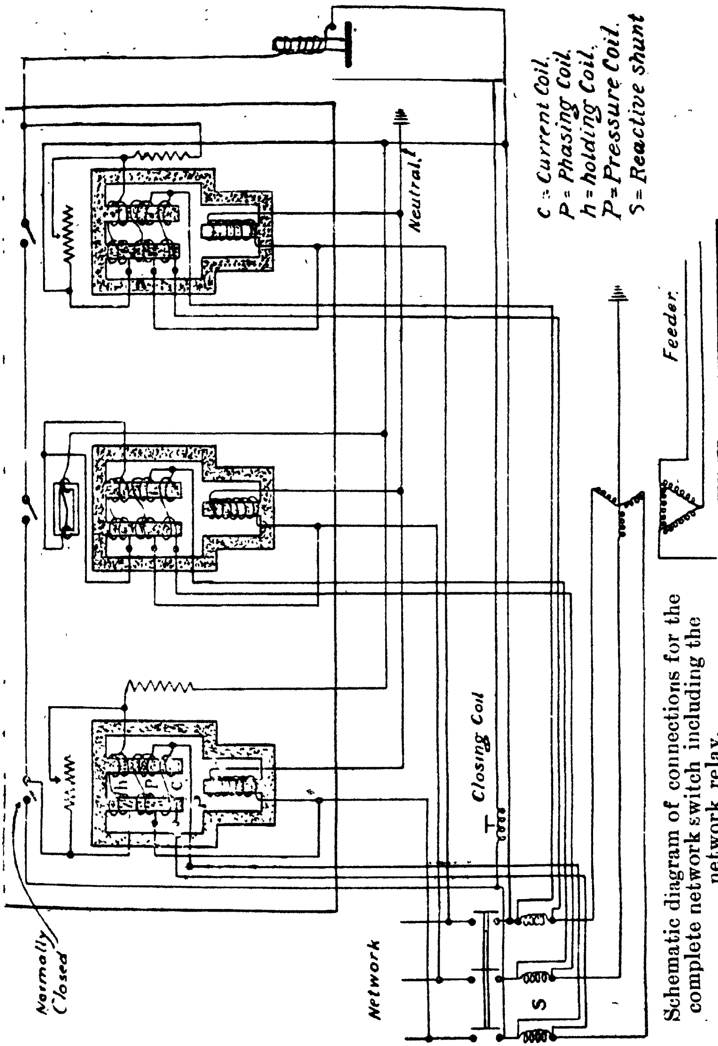
This relay is used with a special circuit-breaker and an auxiliary relay.

Construction :—This relay operates on the induction principle, and the principle of the moving element is similar to any type of induction relay described before. Its main parts consist of :—1. The Electromagnet. 2. The Damping magnet. 3. The moving element. 4. Contact assembly. 5. The resistor or reactor element. 6. Case and cover.

The moving parts of the relay consist of a copper disc mounted on the standard pivot arrangement. A stop limits the travel of the disc to 180 degrees. The shaft of the disc is connected to the moving contact through gears. A spiral spring mounted on the shaft on which the moving contact is mounted, serves to keep the contacts closed as long as the relay is completely de-energised. The standard silver contacts are used, the stationery one being spring-mounted and so adjusted as to have a slight compression when contact is made with the moving one, thus insuring a good contact. The resistor or reactor unit is mounted above the moving element, the mounting for the two units being the same so that they are interchangeable.

The main coil situated on the lower pole is a standard potential coil wound for 110 volts. The coils on the two upper poles consist of three sets, one set of holding coils and one set of current coils. The relative location of these coils is shown on wiring diagram in Fig. 10·26. The holding coils consist of a large number of turns of fine wire, and the current coils at the lower end of the poles consist of a few turns of heavy wire.

Operation and Characteristics:—Fig. 10·28 shows a schematic diagram of connections for the complete network switch including the network relay. This diagram shows the connection for a 3-Phase, 4-wire circuit. The no-voltage coil and the closing coil are included in the switch equipment external to the relay. The normal position of the contacts in the relay, with the coils de-energised, is loose, the contacts being held closed by the action of the spiral spring connected to the disc shaft. Fig. 10·30 shows the connections of the relay more clearly. Referring to this figure, when the distribution transformer is energised, the circuit-breaker no-voltage release coil is energised, drawing up its plunger and closing the circuit of the closing coil thus closing the network switch and connecting the transformers to the network. As soon as these switches are closed, the main potential winding of the relay is energised, it being connected across the line on the network side of the switches. This potential winding of the relay is such that it produces sufficient torque in the disc to cause the relay contacts to open when it alone is energised. The current coils of the relay are connected across a special reactance shunt in the main line, and serve to keep the contacts closed even against the torque created by the voltage element, as long as current is flowing through the shunt into the network. The holding coils are connected across the line in series with the relay contacts, and also serve to keep the contacts closed against the torque of the main potential winding, the action aiding that of the current coils when load is flowing, and serving to keep the switch closed under conditions where there is no current flowing in the line. The current coils serve a second purpose of that of opening the contacts whenever the direction of flow of current in the switch is reversed. The phasing coils serve the purpose of "Bucking" the torque created by the main potential winding and thus closing the contacts when the transformer potential is at least $\frac{1}{2}$ volt greater than the network potential, and when the phase relation between the transformer voltage and the network voltage is correct. With the current flowing in the



Schematic diagram of connections for the complete network switch including the network relay.

Fig. 10'28

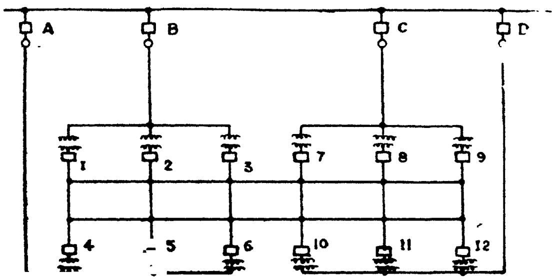
current coil in the reverse direction, the action of the holding coil is "bucking" that of the current coil, and

thus the value of reverse current, at which the relay will open its contacts may be adjusted by means of adjusting the resistance of the holding coil.

The small tungsten filament phasing lamps connected in series with the phasing coils increase the sensitivity of the relays and prevent the coils from burning out when full voltage or twice full voltage is impressed upon them. The phasing coils have to be designed to give the desired operation at a very low voltage and thus, unless extra resistance is inserted in the circuit, are damaged by high voltage. The tungsten filament lamps introduce a low resistance in the circuit as long as the current flowing is small and the filament kept cool. However, when it is subjected to high voltage, the current increases until the filament becomes such as to limit the current to a safe value.

Fig. 10·29 shows a schematic diagram of a low voltage A. C. distribution network as used with the network relay described above. Referring to this figure, the action of the relay when installed in a network system may be followed out. Suppose the complete network in fig. 10·29 is dead. The network switches will now be in the open position, but the network relay contacts will be closed, due to the action of the spiral spring. Thus when any of the L. T. feeder switches *A*, *B*, *C* or *D* is closed for example if switch *B* is closed, the relays on the network switches Nos. 1, 2, 3, will allow the switches to be closed, thus energising the network. At the same time the voltage coils of the remaining relays Nos. 4 to 12 will be energised, thus opening the contacts on these relays. In order to have any of the remaining network switches closed, when the primaries of the distribution transformers to which they are connected are energised, there must be at least $\frac{1}{2}$ volt difference across the opened switch in phase with the network voltage, in order to energise the phasing coils sufficiently to overcome the torque created by the potential coils, and thus close the contacts of the relays. Thus circuit-breaker *A* may be closed before the load on transformers Nos. 1, 2, & 3 becomes such that the network voltage drops at least $\frac{1}{2}$ volt below that of the bus bar voltage, but the relays will not close their contacts

and consequently the switches Nos. 4, 5 and 6 will not be closed. The switches will close, however, as soon as the load on the network becomes great enough to cause the drop across the open switch when the transformers are energised from the high voltage side. A similar condition will exist when switches *C* and *D* are closed. This feature of the relay enables the operator to maintain most economical conditions on all distribution transformers.

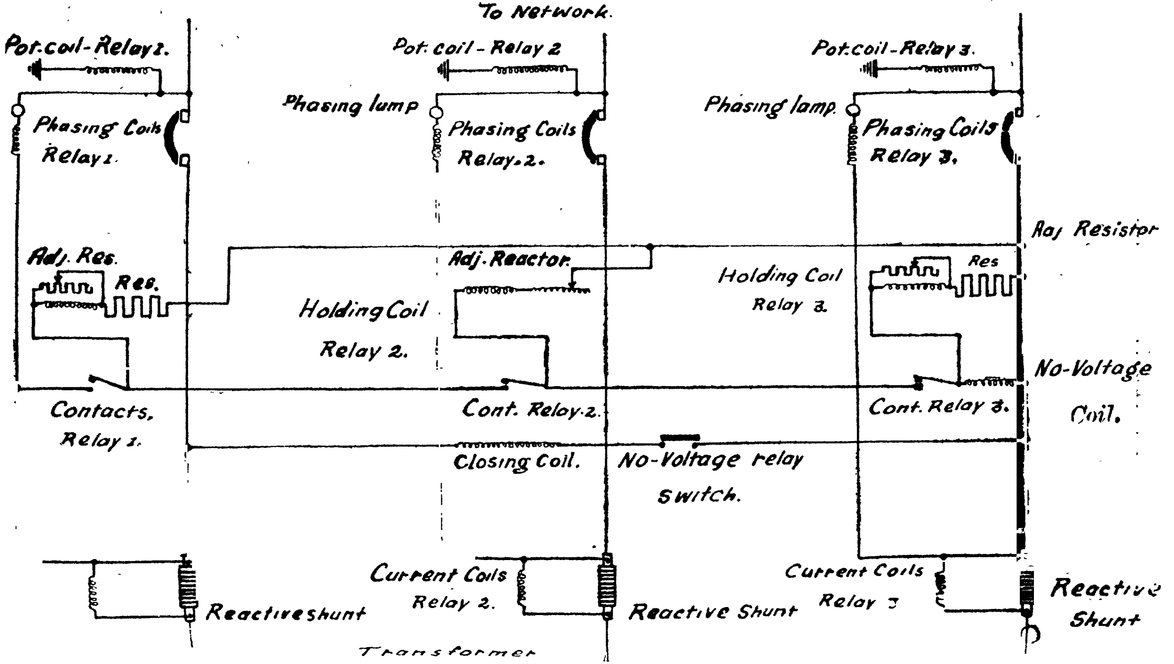


Schematic Diagram of A. C. Low Voltage Distribution Network.
Fig. 10 29.

When one of the breakers *A*, *B*, *C* or *D* at the substation is opened, as would be the case at times of light load, magnetising current will flow from the network to transformers on the disconnected feeder. This flow of magnetising current produces sufficient torque in the relays to cause them to open their contacts and thus open the network switches. Therefore, opening a feeder breaker will cause all distribution transformers on that feeder to be disconnected from the network. This saves the iron losses of a considerable number of transformers at times of light load and also provides a means whereby any feeder may be disconnected for repair work at times of light load, without discontinuing service on the network.

In order to illustrate the protective feature of the relay, suppose circuit-breakers *A*, *B*, *C* and *D* are all closed and likewise all of the network switches. If a fault develops in any of the feeders *A*, *B*, *C* or *D* as at *X*

Fig. 10.30



To Network.
Pot.coil-Relay 1.
Pot. coil - Relay 2
Pot.coil-Relay 3.
Phasing lamp
Phasing lamp.
Phasing Coils
Relay 1.
Phasing Coils
Relay.2.
Phasing Coils
Relay 3.
Adj. Res.
Res.
Adj. Reactor.
Holding Coil
Relay 2.
Holding Coil
Relay 3.
Res
Adj Resistor
No-Voltage
Coil.
Contacts,
Relay 1.
Cont. Relay 2.
Cont. Relay 3.
Closing Coil.
No-Voltage relay
switch.
Current Coils
Relay 2.
Current Coils
Relay 3
Reactive shunt
Reactive Shunt
Reactive
Shunt
Transformer

for example, the current will immediately begin to flow from the network towards the fault, thus reversing the flow of current through the current coil in the lines 1, 2, and 3. This will immediately open the contacts of relays on lines 1, 2 and 3, thus disconnecting the faulty feeder from the network without disconnecting the service on it. The action of the relay must necessarily be very rapid in order to disconnect the line before the overload relays on the lines *A*, *C* and *D* operate to disconnect the entire network.

The current in the holding coil (Fig. 10·30) must be 90 degrees out of phase with the current in the main potential coil in order to have the maximum torque for holding the contacts closed. When connections are made to a 3-phase circuit, it is therefore necessary to consider the phase relation between these currents in order to insure the satisfactory operation of this relay. As shown in Fig. 10·30, the potential coil may be connected between each line and ground when the secondary of the transformer is star-connected with the neutral grounded. With these connections, it is necessary to introduce a reactance in series with the holding coil of one of the 3 relays instead of the resister. Thus, the relays are supplied with either an adjustable resister or adjustable reactor in series with the holding coils in order to secure the proper phase angle for good operation.

Summarising briefly, this relay, which controls the operation of the network switch, performs the following functions :—

(1) With the network dead, the relay allows the network switch to close and connect the distribution transformers to the network as soon as the transformers are energised from the side.

(2) With the network alive and the network switches open, when the transformers are energised, the relay causes the network switches—

(*a*) to close when the transformer voltage is ½ volt or more, algebraically, than the network voltage and it is in phase with the network voltage.

(b) to remain open when the transformer secondary voltage is equal to or less than the network voltage, or when it is different in phase from the network voltage or is reversed.

(3) With the network alive, and network switches closed, the relay must prevent the switch from operating until the flow of energy is reversed, *i. e.*, the flow is from the network to the transformer.

(4) With the network alive and the network switch closed, the relay must open the switch

(a) when reverse energy flows due to non-inductive load of the following amount :—

For	12·5 K.V.A.,	220-volt	transformer	0·25	amp.
„	25	„	„	0·5	„
„	50	„	„	0·75	„
„	100	„	„	1·5	„

(b) when reverse energy flow occurs due to the magnetising current of the transformer to which the network unit is connected.

(5) In the case of a short-circuit in the primary cable or within transformer, the relay opens the switch quickly due to the reverse energy flow, and disconnects the transformer from the network. The switch must open in 0·2 of a second in order to obtain time selectivity with the substation overload relays and in order that correctly rated fuses in the transformer circuit will not blow under short-circuit conditions.

586. Pilot Wire Protection Scheme for Network :—Pilot wire schemes can be used in connection with time-limit over-current directional scheme, where the number of substations is too great to use that scheme exclusively.

There are two types of pilot wire schemes :—

(1) Circulating current,

(2) Opposing voltage,

Selection of pilot wire scheme :

(1) Pilot wire scheme should not unnecessarily displace the time and direction scheme which usually is less costly on account of not requiring pilot wires.

(2) Since the cost of pilot wire is proportional to length, the shortest ones could preferably be the ones protected by pilot wire scheme.

(3) Pilot wire relays are not quite instantaneous, so that they should be on sections that are not required to open ahead of directional relays having the shortest time setting. That is, they should be rather far from the generating station.

(4) There is a limit of the length of the pilot wire that can be used ; because, the sensitiveness decreases as the lengh is unduly increased unless the size of the wire is increased by a prohibitive amount.

Pilot wire schemes require special type of transformers which can not be used with relays nor with instruments. Relays are usually adjusted to operate on fault current of 25 to 50 per cent of the rated load current.

587. The Advantages and Disadvantages of the Pilot Wire Scheme :—

Advantages.	Disadvantages.
1. Not affected by through faults.	1. Cost of pilot wire.
2. Operates on fault currents that are small compared with load current.	2. Cost of current transformers having special characteristics.
3 Operates almost instantaneously and not interfering with successive time settings employed in other part of the system.	3. Difficulty in getting current transformers of exactly similar characteristics.
4. Discrimination well on short lines.	4. Possibility of undetected break in pilot wire.
5. Not requiring any other special device for ground protection.	5. Possibility of false operation due to voltage in pilot wires induced by short-circuit current in the neighbouring wires.
6. Simple construction.	
7. No potential connections necessary.	

588. Circulating Current Pilot Wire Scheme:— This scheme can be used only in short lines in order to decrease the drop in the pilot wire due to heavy short-circuit current. The transformers used in this scheme have secondary ratings of 0·5 or 1 ampere, so, that the pilot wire drop is less than it would be with 5 ampere secondary.

589. Merits and Demerits of Circulating Current and Opposing Voltage Scheme.

Circulating current.	Opposing voltage.
1. Open circuit in pilot wire results in tripping the circuit-breaker.	1. Open circuit in pilot wire prevents automatic tripping of circuit-breaker.
2. Short-circuit in pilot wire prevents automatic tripping of the C. B.	2. Short-circuit in pilot wire trips the C. B.
3. Charging current may trip the C. B. in case of heavy through short-circuits.	3. Charging current may trip the C. B. in case of heavy through short-circuits.
4. Induced voltage from the neighbouring power line may trip the C. B.	4. Induced voltage may trip the C. B.
5. Each C. T. normally has a low voltage in its secondary, but in case of heavy short-circuit, or while the circuit-breaker is being opened on local fault, the voltage may be high.	5. Each current transformer has a very high voltage on its secondary on normal currents. On heavy through short-circuits the voltage is still higher, but it is lower when ordinary faults occur on the section that is protected.

590. McColl Circulating Current System with Biased Relays for Feeder Protection.

AB—Feeder joining either power-station to substation or substation to substation.

$C.T._1, C.T._2$—Current transformers at each end for the feeder.

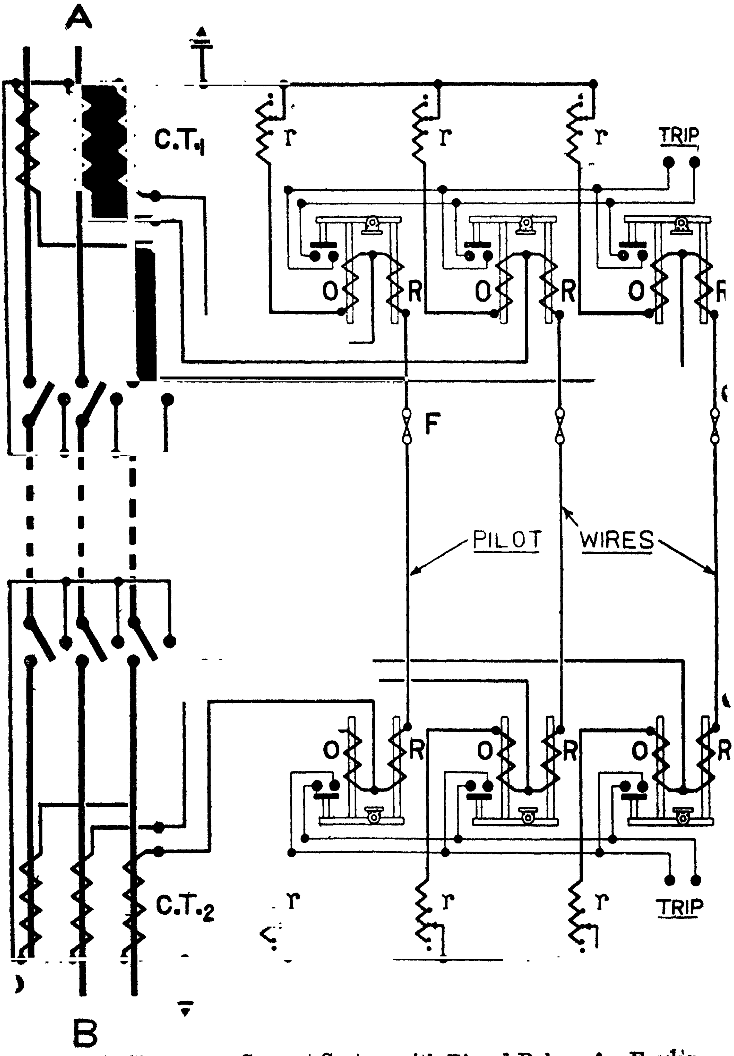
O—Operating coil of the beam relay.
R—Restraining ,, ,, ,, ,,
f—Fulcrum of the beam.
r—Resistance in series with the operating coil whose value is equal to half the resistance of each pilot wire. This affords equal current to flow through the operating and restraining coil under normal working conditions; hence, the beam is held down by *R*, and trip contacts remain open.

F—Fuse which will melt when more current circulates through the restraining coils and pilot wires due to overload.

Let *A* be the supply end of the feeder. Under fault conditions, the output of $C.T._1$ will be more than that of $C.T._2$. The difference between these current outputs flows through the operating coil circuits, thereby increasing the current strength in those circuits. This operates the relay and closes the trip coil circuit and opens the oil-circuit-breaker. The desired degree of stability is obtained by biasing the relay. This may be accomplished either by giving more leverage to the restraining coil or by increasing the resistance in the operating coil circuit. The effect of increasing the resistance in the operating coil is to divert more current through the restraining and pilot wire circuit. The biasing thereby allows a time delay of operation of the relay.

This shows that for slight difference of current flow, the relay will not operate. Generally, it is desirable to give 10% biasing.

The capacity current of the pilot wires traverses only through the restraining coil of the relay. This increases the stability of the relay.

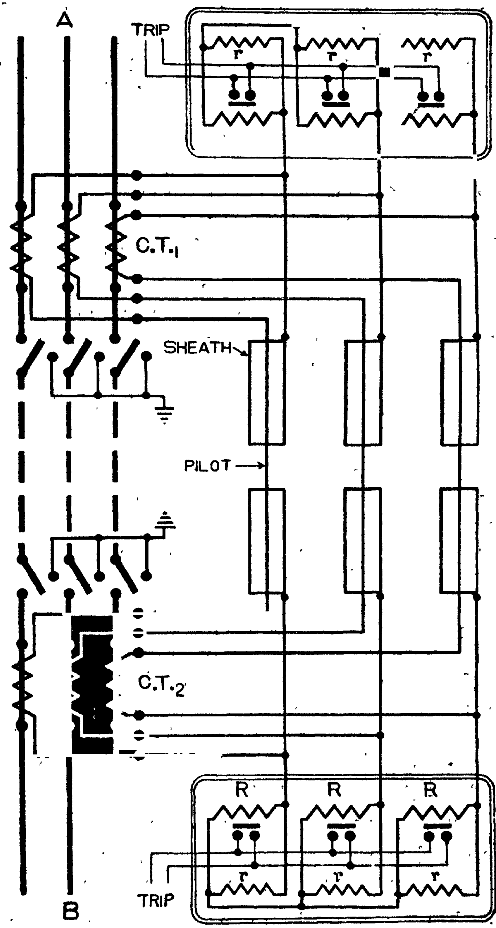


McColl Circulating Current System with Biased Relays for Feeder Protection

Fig. 10·31

The fault setting of the relay, connected to out-going feeders should be more than that of the in-coming feeders.

591. Opposing Voltage Sheath Pilot Wire Protection Scheme (Beard Hunter).—The secondaries of the current transformers at each end of the feeder are connected in series with pilot wires and relays, so that under normal conditions, their opposed voltages balance and no current flows through the relays to operate them. But the capacity current of the pilot wires at normal frequency forms a direct out of balance current which changes with



Beard Hunter Sheath Pilot Wire Opposing Voltage Protection System for Feeders.

Fig. 10·32

the straight through current and may cause operation of the relay. The difficulty of the capacity current can be overcome by using pilot wires with sheaths. The sheaths are interrupted in the centre as shown in Fig. 10'32. From the study of the diagram, it will be found that the capacity current will no longer flow through the relay coil. Oscillatory troubles are sometimes produced due to mechanical shock and electrical transients. These may be overcome by shunting the relay coils with non-inductive resistance *r*, which increases the fault setting, because, high frequency current will take easier path through non-inductive resistances.

The cost of the sheath pilot cables is nearly twice the ordinary pilot cables, but if they are used in conjunction with the telephone communication cables, it is about 40 per cent. more costly.

9952. Transmission Line Troubles and their Remedies.

Troubles and Causes :—Lightning, the sudden switching of loads and other atmospheric phenomena cause disturbances on the line conductors. The disturbances encountered on the transmission lines are the production of high voltages which occur in the form of a static charge over the whole transmission system or a high frequency surge or a travelling wave of high potential. The first of these, namely the static charge is due to the approach of a charge cloud near the line conductors. This induces an enormous uniform distribution of pressure along the line due to the line conductance, thereby, raising the line potential to many times the normal potential or voltage.

The sudden switching of loads on to an uncharged line and the wrong synchronising of alternators are the chief factors which give rise to high frequency surges.

The third and the most frequent disturbance namely, the occurring of a travelling wave of high potential induced in the line is due to the sudden changes which take place when lightning flashes occur.

Remedies.

(1) **Static Charges :**—In the station installation, the troubles due to the occurrence of static charges have been multiplied by the Delta-Star connection of the power transformer (Δ-$L.T.$—γ-$H.T.$), the star connection being on the transmission side with neutral point of the star being earthed. By this means, any static charge leaks away to earth without raising the voltage.

(2) **High Frequency Surges** :—Troubles arising from high frequency surges are kept at minimum by avoiding the sudden switching of loads on to the lines as far as possible and by the correct synchronising of alternators, as these are the two main causes, if unattended to, give such troubles.

(3) **Troubles due to Lightning Flash or Lightning Strokes** are the most frequent occurrences on high tension overhead lines, and all the means are restored to keep them at bay. It is a fortunate and a healthy coincidence that the want of any protective device to free an overhead line from damage due to a direct lightning stroke has been compromised by the very rare occurrence of such direct troubles, especially when an earth wire is running over the line conductors. But the equally dangerous and the frequent ones are the results of high lightning flashes in the neighbourhood of lines.

The phenomenal troubles take place in this way: when a lightning flash takes place, the potential of the clouds concerned reduces to zero ; the immediate change in the electrostatic field induces a large charge in the line conductors and this charge travels freely along the conductors with almost the velocity of light with very high potential. If these disturbances were to occur at a remote part of the overhead line, much danger is not felt at the ends of the transmission line. But the consequences are great if this surge is to start close to the ends of the line, since, energy may not be absorbed or dissipated before it reaches the turns of the transformers. Here, as the high reactance of the transformer-turns does not allow the progress of the voltage wave any more, the voltage increases considerably to such an extent as to puncture the

insulation of the transformer-turns and thus, work a havoc of the transformer. (*Vide* Lightning Arresters).

To safe-guard from such calamity, the main protective devices adhered to are :—

(1) To install lightning arresters which relieve the lines of the high voltage waves by taking them to earth. (See further.)

(2) To insulate heavily the first few turns of the high tension transformers which have to bear the attack.

593. Failure of Insulation, Leakage Protection:—The two main causes of failure of the insulation in any part of the circuit are :—(1) Damage to the insulation caused by overheating due to overload or short-circuit, (2) Stress in the insulation caused by voltage higher than it can withstand in its normal condition, such excessive voltage arising out of the causes stated before. The possible failure of insulation introduces danger to life from shock ; and in other cases, where the failure is caused by the admission to or near the circuits of possible flow of leakage current, may cause damage by electrolysis, char surrounding insulation, woodwork, etc., and thus introduces risk of fire, or may result in a short-circuit with all its serious consequences. The failure of insulation is prevented by avoiding the causes of failure mentioned above.

The only safe course when insulation has failed, is to isolate the affected portion of the circuit and repair the insulation. A single failure of insulation between a conductor and earth may exist theoretically without affecting operation of the system, provided the insulation be prefect in the rest of the circuit. In actual practice, however, the failure subjects the isulation of the other lines to the full voltage of the system, and the danger to life from shock is consequently increased. With the earthed neutral, an earth fault on any line will form a short-circuit through the resistance of the fault and the neutral earth connection.

Several faults may also exist simultaneously without disturbing operation theoretically, so long as they all

lie on the same pole or phase. But as a matter of fact, under such conditions, a pressure difference of even 10 to 15 volts between two points in a wiring system (much more in other cases) is sufficient to cause considerable leakage under favourable conditions (Cf. Rail return in traction systems).

A milli-ammeter connected between the conductor and earth may be used for measuring the leakage current between a nominally insulated conductor and earth. If the total leakage current exceeds 1/1000 of the maximum current supplied, steps should be taken to locate the leakage and improve the insulation of the system.

Most often, the leakage from a faulty system attains to a dangerous limit long before it is sufficient to operate overload-protection devices. It is desirable, therefore, that the faulty section should be isolated automatically by a leakage-protective device. This generally consists of a relay which is acted on by the leakage current itself, or it may act on the principle that when there is leakage, the algebraic sum of the currents in the three conductors of a three-phase system is no longer zero.

The Howard leakage detector has a current transformer connected to the earthing wire of, say, a switchboard frame, the secondary being connected to a tripping relay. So, any leakage current to earth from the bus-bars is carried by the transformer, and the relay trips, and the circuit-breaker automatically puts the defective conductors out of circuit.

The Ferranti-Field leakage-protection system for cables has an iron-cored coil surrounding the three-phase cable to be protected, and this coil is connected to the trip-relay. If there is leakage from any one of the cable cores, the algebraic sum of the currents in the latter is no longer zero, and as such, a resultant flux traverses the iron core inducing an E. M. F. in the coil which operates the relay.

594. Temperature Indicators :—It is of great value to know the temperature of certain parts of generator and transformer windings that are inaccessible for thermometer measurements. An instrument known as

the temperature indicator has been produced to determine these temperatures. Copper coils of known resistance are placed in the parts whose temperature it is desired to know. The changes in resistance are shown on the scale of the indicator, which is marked in degrees Centigrade corresponding to the change in resistance.

The methods of measuring temperature are as follows :—

Method 1.—Thermometer Method :—This method consists in the measurement of the temperature by mercury or alcohol thermometers, by resistance thermometers, or by thermo-couples ; any of these instruments being applied to the hottest accessible part of the completed machine. This method does not include the use of thermo-couples or resistance coils imbedded in the machine as described under Method 3.

Method 2.—Resistance Method :—This method consists in the measurement of the temperature of windings by their increase in resistance. In the application of this method, thermometer measurements shall also be made, whenever practicable, without disassembling the machine, in order to increase the probability of obtaining the highest observable temperature. The measurement indicating the higher temperature shall be taken as the " observable " temperature.

Method 3.—Imbedded Temperature—Detector Method :—This method consists in the measurement of the temperature by thermo-couple or resistance temperature detectors located, as nearly as possible, at the estimated hottest spot. When this method is used, it shall, when required, be checked by Method 2. The highest observable temperature obtained from the readings of the imbedded detectors shall not exceed the values permitted and the highest observable temperature obtained by Method 2 shall not exceed the values permitted by the Rules for Method 2.

595. Temperature Protection :—

Temperature protection is better than any other preventing trouble for mechanical overload, because, ultimately the temperature and not the current damages the machine in large industrial motors. Devices offering this protection are constructed and connected so that the temperature of their heating elements follows the hot spot temperature of the motor. However, this scheme does not adequately protect against internal motor faults so that some other protection is necessary along with temperature protection.

An ordinary lamp may be considered as a crude temperature device but its thermal capacity is too low to give temperature characteristics. Various other simple lamp devices may also be used which are available, their characteristics corresponding a little more closely to the motor heating. One of these is a protective plug comprising of a small heating coil, a fuse and a contact. In operation, after an overcurrent has continued for sometime, the heating coil melts the fuse which releases the contact.

Where the importance of the apparatus to be protected warrants more expensive protective system, some kind of temperature relay can be used. Some of these relays are refinements of the temperature device above mentioned having current adjustments and in some design having adjustments of thermal characteristics by which the operation of each relay is made to conform to the heating characteristics of an individual motor. Other relays combine the thermal principle with current setting so that they do not operate unless both overcurrent and high temperature exist simultaneously.

Temperature relays may be used either to trip the motor off the line or simply to close an alarm circuit. They are suitable for any type of motor but their use is ordinarily but not necessarily limited to motors of larger sizes. Thermal protection is most useful (1) when the motor must operate on over-current as long as is safe, and disturbance to other service is not prohibitive, and (2) where the motor is subject to frequent momentary mechanical overloads.

Cooling of Alternators:—Practically all of the generator-losses appear as heat in or about the windings. To maintain these at a safe working temperature, a cooling medium must be employed to remove the heat as rapidly as it is formed. Air has been the medium generally used. The rotor may or may not be able to produce its fan action, depending on the size, speed, and construction of the rotor. In some cases, chiefly for the very slow speed hydraulic units, it has been necessary to supply an external fan to move sufficient air through the windings. The ventilating air is usually brought from outside the building through a duct and discharged from the alternator directly into the turbine-room or into a discharge duct.

Example 9. What volume of air at 60° is required to cool 25,000 kW. alternator of 96·4% efficiency without more than 26°C rise in air temperature ?

Solution—

Heat to be absorbed per minute

$$= \frac{25 \times 0{\cdot}036 \times 1{,}000 \times 60}{0{\cdot}964 \times 1{\cdot}055}$$

$$= 53{,}500 \text{ B.T.U.}$$

Sp. heat of air $= 0{\cdot}24$ B.T.U. per lb. per °F.

Temp. rise is $26° \times \frac{9}{5} = 46{\cdot}8$ °F.

$$\text{lbs. of air per min.} = \frac{53{,}500}{46{\cdot}8 \times 0{\cdot}24} = 4{,}760.$$

$$\text{Vol. of air} = \frac{4{,}760 \times 53{\cdot}37 \times 520}{14{\cdot}7 \times 144}$$

$= 620{,}000$ cu. ft. of air per min.

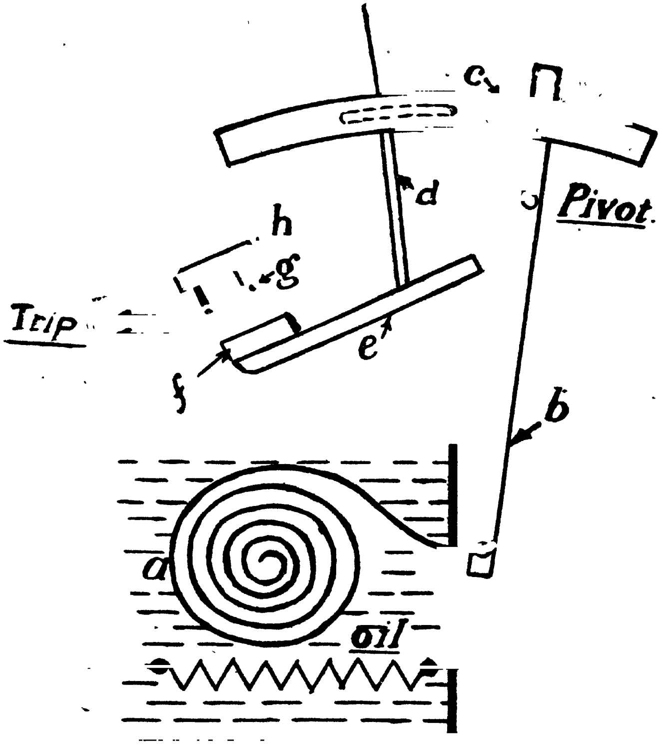
Air-cooling of Generators at Shivasamudram:—The power generated by different generators are conducted to transformer station through heavy cables of 750,000 circular mils and 1,000,000 circular mils. A lean-to 8 feet wide is connected parallel to the generating station for this purpose. To keep down the temperature

of the cable-duct, where the heavy power transmitting cables pass, a number of blowers is regularly arranged to blow in cold air. Cool-air to the pit of the generator is drawn from the lean-to, where five blowers giving 145,000 cu. ft. per second are installed for blowing in air at $\frac{1}{2}$ oz. pressure into the lean-to for also ventilating purposes into the generating station. The generator cables are carried into the lean-to from the generator pit in a duct two feet square.

Ventilation:—A series of fans mounted on a revolving field of suitable design strong enough not to break off under any conditions of operation is included so as to draw the air into the rotor from the out-board bearing side. The air will then pass through the ventilating ducts in the stator core and despatch through the opening in the stator frame. The hot air is let out through the openings all along the periphery of the generator frame above the floor level.

596. Thermal Relay :—The thermal time element relay is designed to give a thermal characteristic similar to that of the apparatus it is desired to protect. In the automatic sub-station, this relay is used to protect the rotary and transformer from becoming dangerously overheated. The design of the relay is such, that the deflection of the moving element is responsive to the R.M.S. value of the load, and thus, it is possible to set the relay to allow the full thermal capacity of the machine and transformer to be taken in peak or continuous loads. The contacts of the relay are connected across the master contactor and thus should the thermal relay operate, the particular equipment is shut down. As soon as the relay is cooled down, however, the equipment is allowed to reset, if required.

Construction :—Fig. 10'33 illustrates diagrammatically the construction of this relay. The moving element consists of a series of bimetal springs (*a*) (one is shown in the sketch) fixed to a pivoted shaft (*b*). At the top of this shaft is mounted a segment (*c*) with a slot cut in the periphery. A pin (*d*) fixed to contact arm (*e*) is located in



Thermal Relay.

Fig. 10·33

this slot. As the shaft (b) is rotated, the pin (d) and consequently the contact arm (e) are carried round. Contact arm carries a bridging piece (f) which makes a circuit tween two fixed contacts (g). The latter are carried on adjustable arm (h), which can be set to a mark on a

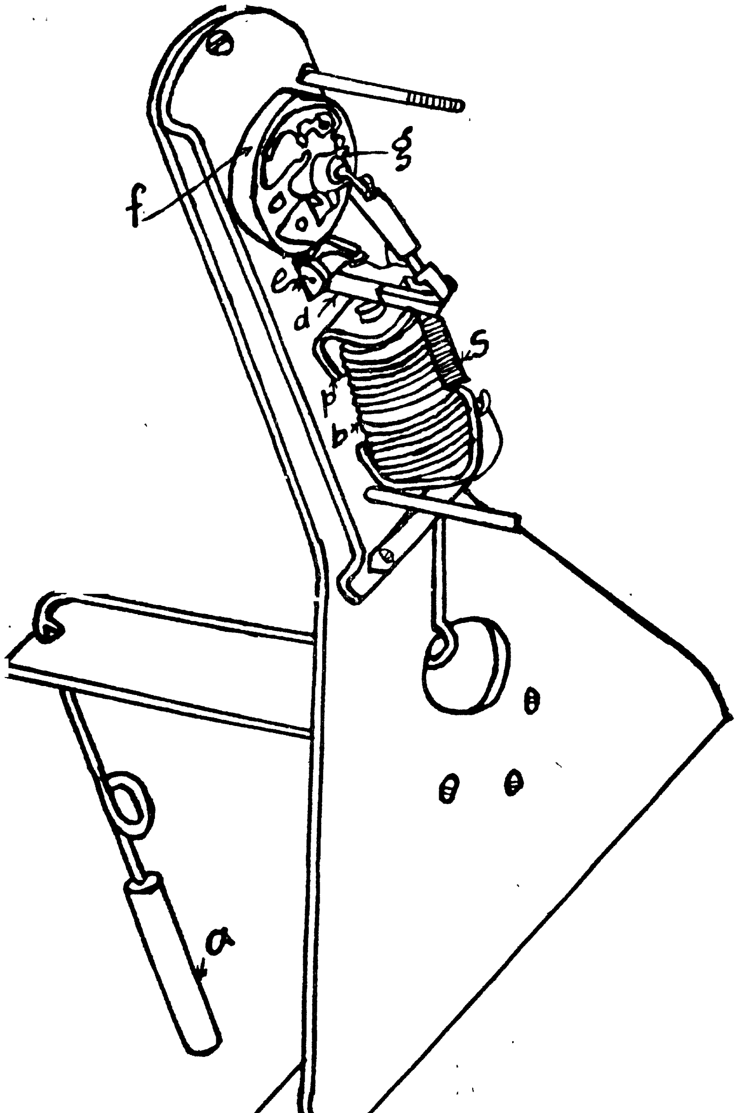
top plate as desired. A spring catch is also fitted to arm (*h*), which engages with a cam (not shown) fixed to the moving contact arm (*e*).

The heating element is located below the relay movement and consists of resistance wire wound in spirals. The heating element and the bimetal springs (*a*) are mounted in a container filled with oil.

Operation :—In operation, the relay is connected, as in the secondary circuit of a current transformer connected in the main low tension lead to the rotary. The current flowing through the relay is thus directly proportional to the load on the machine. The heat produced by the heating element warms the oil which in turn tends to make the bimetal springs unroll, thereby deflecting the contact arm (*e*). The purpose of the oil is to conserve the heat produced, and thus the deflection at any time is relative to the heat in the machines and transformers.

By the arrangement of segment (*c*) and pin (*d*), a time delay, after the relay is operated, is provided before the contacts open, so as to allow the machine and transformer to cool down sufficiently before being connected to the load again. The contacts are held closed during this period by the action of the spring catch slipping over the cam. This motion also provides a quick break on the contacts as they are not released until sufficient torque has been produced by springs (*a*) to deflect spring over the cam.

Adjustment :—Remove the screw from the filling hole (immediately above the inspection window). The relay is set to suit the thermal rating of the machine and transformer, which are usually 25 °/o overloaded for 2 hours. Should a higher or lower rating be required, the arm (*h*) can be moved to right or left increasing or decreasing the travel of the moving contacts. On test, the relay is set to disconnect the machine from the loads when this capacity has been reached, and this setting is marked on the top plate of the relay.



g
f
e
d
S
p
b
a

597. Bearing Thermostat and Grid Thermostat :—The purpose of a thermostat is, on a temperature attaining a pre-determined value, to close a circuit whereby an alarm indicator or relay is controlled. In automatic equipments, thermostats of two types are used.

(1) **Bearing Thermostats :**—Which are supported on bearing pedestals of machines. They are arranged so that, in the event of bearing developing a rise in temperature due to presence of a defect. the thermostat will complete the circuit of a **lock-out** (Hand-resetting) **relay,** which in turn de-energises the master relay controlling the automatic equipment, shutting down the machine affected. The faulty bearing is located, by observing which of the thermostats is in the closed position. After it has received attention both the thermostat and lock-out relay are reset by hand.

(2) **Grid Thermostats :**--Which are carried by brackets above the load limiting resistances, should overload conditions persist long enough for the grid to heat up to a pre-determined temperature ; thermostat will operate to close its contacts, thereby de-energising the master relay, thus closing down the machine affected. As soon as the temperature has fallen sufficiently, the thermostat will reset itself permitting the machine to be restored to service. Fig. 10·34 illustrates the construction of a Grid Type thermostat. The Bearing Type differs from this, only in mounting details.

Construction :--The thermostat consists of a liquid container or bulb (*a*) connected by copper tube to seamless copper bellows (*b*). The bulb of the Bearing Thermostat is located in a hole just below the surface of the bearing lining and that of the Grid Thermostat is hung about one inch above the resistance grids A projection (*p*) is provided on the top of the bellows (*b*). A lever (*d*) pivoted at (*e*) and retained by spring (*s*) controls the switch (*f*) with the contacts (*g*).

Operation :—An increase in temperature to a pre-determined value will cause the liquid in the bulb (*a*) to boil, resulting in the expansions of the bellows (*b*). The movement of the projection (*p*) against the spring (*s*)

pushes the lever (*d*) upwards until the switch (*f*) passes over dead-centre and closes contacts (*g*). When the temperature falls, the bellows will collapse and, in the Grid Thermostat, will eventually allow the switch (*f*) to be opened by the spring (*s*), but in the Bearing Type, the lever operating the switch is so arranged that the switch is not opened by the collapse of the bellows but must be reset by hand. The approximate temperatures at which thermostats are arranged to operate, are 85 degrees Centigrade for the Bearing Type and 300 degrees Fahrenheit for the Grid Type.

Inspection :—See that the switch (*f*), when operated, closes its contacts (*g*) and in the case of Grid Thermostat, resets correctly.

598. Lock-out Relay :—In the event of serious trouble, which cannot be automatically cleared, it is necessary to shut down and prevent the automatic equipment from restarting, until the trouble can be investigated. This is accomplished by the lock-out relay, which is energised when the contacts of various protective devices close; the relay short-circuits the operating coil of the master contactor, thereby preventing the latter from closing until this relay contacts are reset by hand.

Construction :—Fig. 10·35 illustrates the construction of this relay. A small contact drum (*a*) carries two moving contact strips (*b*) (only one can be seen in the sketch), which engage with two sets of fixed contacts (*c*) when the drum is rotated. The drum is held in the normal position by a small catch (*d*) pivoted at (*e*) which engages with a pin (*f*) fixed to the drum spindle (*g*). The electro-magnet (*h*) is provided with an armature (*j*) pivoted at (*k*) which carries the tripping piece (*l*). When the electro-magnet is energised, the armature is pulled up and the catch (*d*) is tripped. The contact drum is then rotated by the spring (*m*), and the contacts close.

The contacts then remain closed until the drum is rotated and latched by means of the small resetting knob (*n*).

Drop-Flag Indicator :—For the convenience of an inspector and to enable the cause of any trouble to be

located quickly, six standard drop-flag indicators are provided.

The coils of the indicators are connected in series with the contacts of the devices which operate the lock-out relay. When a protective device closes its contacts, one of the indicators is therefore operated at the same time as the relay. Both the relay and the indicator remain, then, in the operated position until they are reset by hand. The indicators are numbered to correspond with the associated protective devices.

Inspection :—Examine the contacts and clean, if necessary. Make sure that the contact drum latches properly in the normal position. See that the electro-magnet

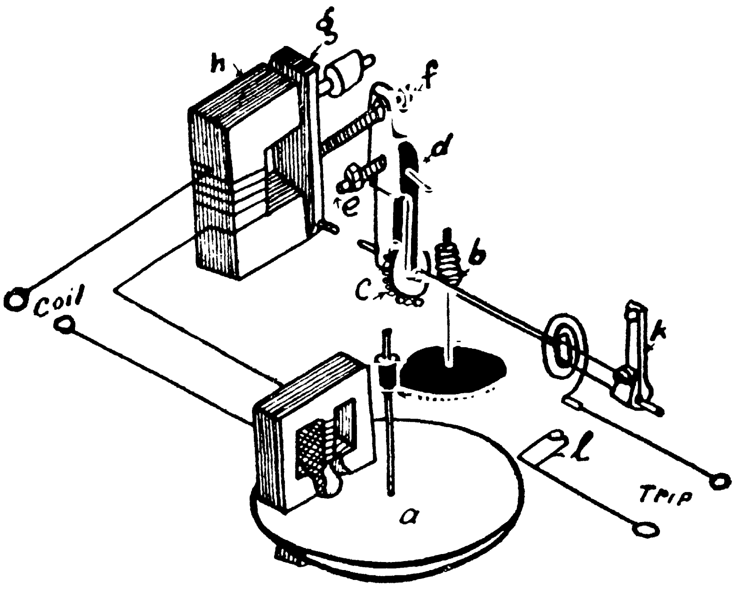


DIAGRAM TO ILLUSTRATE THE OPERATION OF

Time-limit Relay.
Fig. 10'36

armature is free in its bearings and releases the catch drum properly. Do not alter the air-gap of the electro-magnet by interference with the screw (*o*).

599. The Time-limit Relay for Rotary Starting :—The starting of the rotary converter in an automatic sub-station from the control station is to take place in a systematic way and in a definite time; and the time-limit relay is designed to give starting sequence protection to the whole of the automatic plant. This is accomplished by energising the relay immediately the starting sequence commences, and disconnecting it when completed. The trip contacts are connected to the lock-out relay (described before), which is energised if the relay is not disconnected before the time-limit expires.

Construction : –Fig. 10·36 illustrates the construction of the relay. The driving portion consists of an induction-type relay element (*a*), the disc shaft of which drives through a pinion and gear wheel. Fixed to the gear wheel shaft, is a worm (*b*) located so as to be able to engage with a worm wheel (*c*), which is mounted in pivoted bracket (*d*). The latter tends to tilt under the action of a weight screwed to a weight arm (*e*) but is prevented from doing this by a screwed strip (*f*) resting against the armature (*g*) of the electro-magnet (*h*). On the shaft of the worm wheel (*c*), is mounted a contact arm (*k*), which when operated, engages with fixed contact (*l*). An insulated stop for the contact arm is mounted on the front plate in such a position as to give a maximum time delay of 2 minutes For the sake of clearness, the front plate and contact arm stop are not shown. A spring fixed to the shaft of the contact arm (*k*) returns the latter to zero when the worm wheel (*c*) is not engaged with worm (*b*).

Operation :—As soon as the relay is energised, the electro-magnet (*h*) attracts the armature (*g*), thus allowing the worm wheel bracket (*d*) to swivel round until the worm wheel (*c*) engages with the worm (*b*). At the same time, the disc begins to rotate thereby operating, through the reduction gears, the contact arm. When de-energised, the arm (*g*) is released and pushes the

bracket (*d*) to normal position thus, lifting the worm wheel (*c*) out of engagement with the worm. This allows the contact arm (*k*) to return to zero.

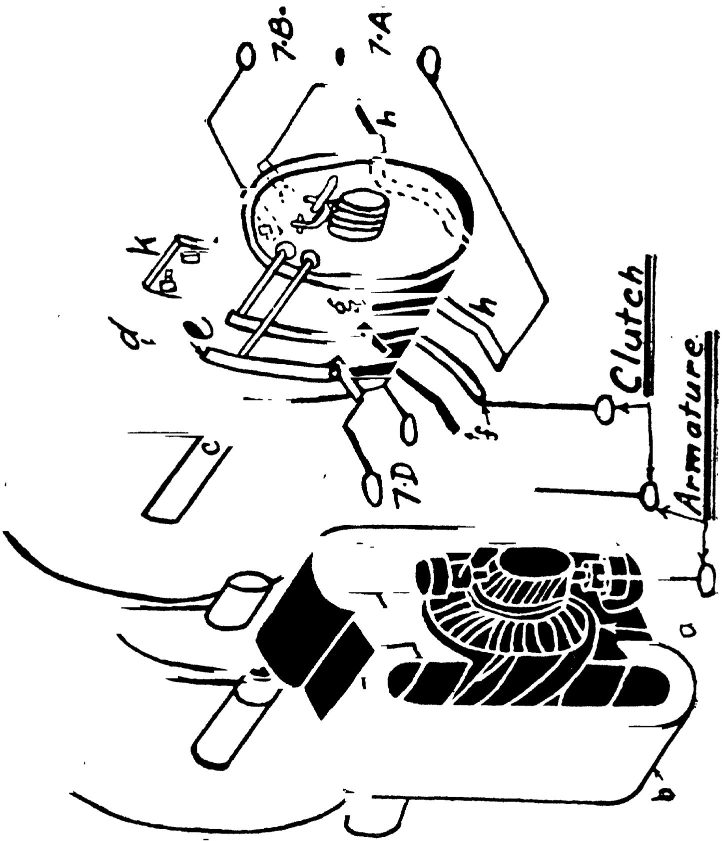
Inspection :—Note that the armature (*g*) is free in its bearings and that it swivels the bracket (*d*), so that, the worm wheel (*c*) is clear of worm (*b*). Examine the contacts and clean, if necessary.

600. Polarised Motor Relay :—This relay is used to ensure that the polarity of a rotary converter in an automatic sub-station is correct, before the same is connected to the D. C. bus-bars. If the polarity of the converter comes up wrong, a pair of contacts (7-*D* are closed (Fig. 10·37), which in conjunction with a field reversing contactor causes the converter 'to slip a pole' thus correcting its polarity. When the polarity is correct, a second pair of contacts (7-*B*) is closed which allows the sequence of operations to continue.

Construction :—Fig. 10·37 shows the construction of this relay. The moving element consists of a small D. C. armature (*a*) which can rotate between the poles of a fixed permanent magnet (*b*). Through a train of reduction gears, the armature operates the clutch shaft (*c*). Mounted on this shaft is the clutch drum (*d*) in which is fixed the clutch coil. The connections to this coil are made by means of slip rings (*e*) and brush (*f*). Contact (7-*A*) is made in the normal position by a segment (*g*) and brushes (*h*). On the clutch drum (*d*), is mounted a contact bridge (*k*), which is carried round to make contacts (7-*D*) or (7-*B*), when the clutch coil is energised according to the direction of reaction of the armature.

A double acting spring is fixed to the clutch drum, which normally holds it in the central position. When the clutch coil is energised, the drum is carried round against this spring, but as soon as the current is switched off, the spring immediately returns the drum to the normal position midway between contacts (7-*B*) and (7-*D*) which also close the contacts (7-*A*).

Operation :—The armature and clutch are connected to the D. C. terminals of the machine through

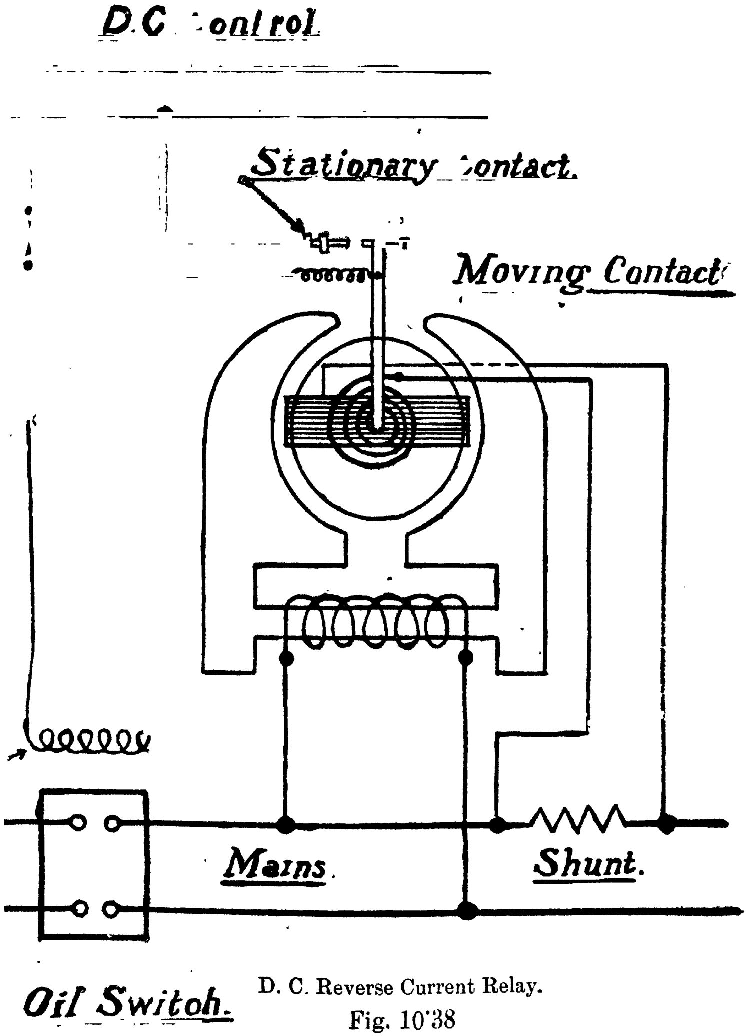


Polarised Motor Relay.

Fig. 10·37

resistances, and as soon as the machine is synchronised, D. C. is delivered to the armature and clutch coil. The latter, when energised, attracts the clutch drum to an iron armature on the shaft (c^1, and thus the drum is carried round with the shaft. The direction of rotation depends

on the polarity of the machine and if the polarity has come up wrong, the armature rotates in such a direction



D. C. Reverse Current Relay.
Fig. 10'38

as to close contacts (7-*D*). When the polarity is correct, contacts (7-*B*) are closed.

601. D. C. Reverse Current Relay :—This is also similar to an overload relay but the main feature of this is that if the current in the circuit reverses, then this relay closes the contacts, a tripping circuit thus tripping the machine switch. This is applied to a rotary converter on the D. C. side to prevent reversal of current. Fig. 10'38 shows the internal and external connections of this relay.

Construction and Operation :—The relay works on the principle of the D' Arsonal instrument. This consists of a moving coil, connected across a shunt in the line to be protected. The magnetic flux to produce torque on the moving coil is produced by a voltage coil wound on an iron yoke as in Fig. 10'38. The cast iron yoke consists of two pieces joined in the rear by a core of small cross-section.

The stationary contact is mounted on a pivoted arm extending from the axis of the moving assembly to the front of the yoke. On the end of this arm, is attached a pointer which extends up over the scale, which is mounted on the front of the yoke.

The voltage winding of the electro-magnet is connected to the line and is of such strength that the core is highly saturated. The control springs are connected so that they exert a slight torque to hold the contacts open. As the relay is practically polarised by the potential coil, the field, set up by the current in the moving coil, will react with the magnetic field, and the moving coil will tend to rotate, the direction depending upon the direction in which the current is flowing. The current coil is so connected that under normal conditions, the torque of the moving coil also helps the springs in keeping the contacts open. When a reverse current occurs, the torque produced by the moving coil opposes the small torque of the springs and thus closes the contacts of the tripping circuit. This will open the machine switch and disconnect it from the bus-bars.

Performance Characteristics:—As the field is saturated, ordinary changes in voltage do not affect the relay's action or calibration. This is well illustrated by

Fig. 10'39, in which is shown a series of curves corresponding to various conditions of setting, (supplied by the manufacturer). The curves *B* and *D* are to be noted particularly, the former being a curve showing the relation at 118 °/o of normal voltage between the time taken for the relay to act and the impressed millivolts (on the moving coil), the relay being set for 5 millivolts, the latter showing the effect of a change in the voltage to 59 °/o of

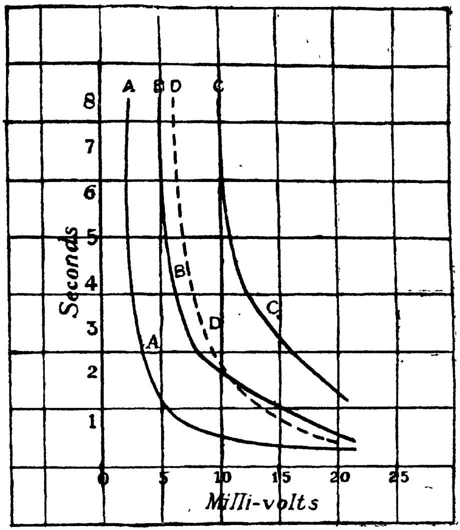


Fig. 10'39

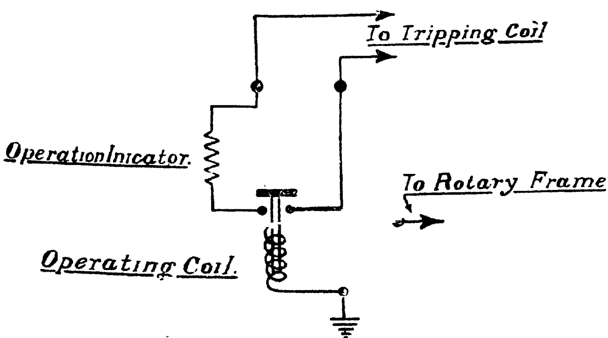


Fig. 10'40

normal, all other conditions being the same. It can be noticed from the curves *B* and *D*, that this change of

50 °/o in voltage causes less than 10 °/o change in the operation of the relay.

These curves also illustrate the inverse time action of the relay. Curve *A* shows that, with a 2-millivolt setting and 2 millivolts applied. 8 seconds are required for the relay contacts to close, while with 16 millivolts applied, only 1/16th of the time or ½ second is needed.

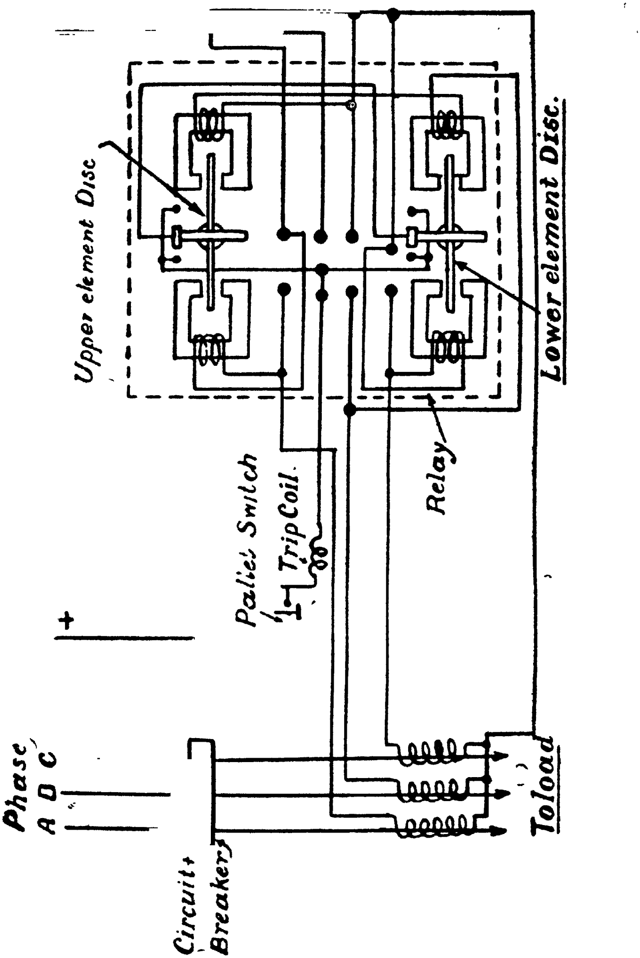
Adjustments :—Adjustments of the relay are made by moving the pointer over the scale, which changes the position of the stationary contact This varies the travel of the moving coil necessary to close the contacts and changes the value of the minimum reverse current necessary to operate the relay. If no shunt is available, the relay may be connected across the length of a conductor sufficient to give the required millivolt drop.

602. Machine Ground and Flash Protective Relay :—This relay is for use on permanently grounded D. C. circuit, for protecting a machine against ground in the armature or flash-over on the commutator. The construction is the same as that of an overload relay. The relay operates instantaneously on 50°/o of the continuous carrying capacity of the winding. The coil will carry, long enough to actuate the relay, a current which is many times the continuous carrying capacity. Fig. 10·40 shows the external connections of this relay applied to a rotary. The operating coil is connected between the machine frame and ground, the frame being ungrounded. With this connection, any current-flow to ground operates the relay which trips the circuit-breaker cutting the machine off the line or locking out the sub-station.

603. Phase Balance Relay :—This relay is used to protect polyphase converters, motors, etc. from operating single phase or with unbalanced phases. It is used largely in automatic sub-station applications.

Construction :—Fig. 10·41 illustrates the internal connections of this relay, while Fig 10·42 shows the external connections. This relay consists of four single phase current elements mounted in a single case. The current elements are mounted in pairs, one pair in the upper part of the case, and the other pair in the lower part.

There are two separate discs, each with its own sets of contacts and, each actuated by one pair of current elements.



External Connections of Phase Balance Relay.
Fig. 10 42

Operation :—The current elements are mounted face to face so that they act on opposite sides of the disc. These elements are so connected that the torque produced by one opposes that of the other. When balanced condition exists in the line, the torques acting on each disc are balanced at every instant. This is, because phase *A* is connected to the upper rear electro-magnets, phase *C* to the lower ones, while phase *B* is connected to the upper and lower front electro-magnets in series. Therefore, the instantaneous current values in all the four electro-magnets are the same and hence, the torque is balanced and no motion results.

If one phase becomes open or overloaded, it will unbalance the mechanical torques of the relay, and one or more pairs of the contacts will be closed. This will energise the trip coil which disconnects the rotary from the circuit.

Characteristics :—Each phase is protected since all the three phases are represented in the relay. One element of one disc is connected in series with one element of the other disc. Thus phase *A* may balance phase *B* on the upper disc, and phase *B* balances phase *C* on the lower disc. This relay is usually supplied with three current taps per phase. With all elements set on the 2-amp. tap, the relay will close its contacts under the conditions. The relay has an inverse definite time curve, the maximum definite time being approximately $\frac{1}{4}$ second.

Adjustment :—This relay of the type described has only the current adjustment. There are three current taps per phase for 2, 4 and 6 amperes. The 2-amp. tap is used for greatest sensitivity. The same tap should be employed on all elements.

604. Construction of the Current limiting Reactors :—These consist of a choking coil which is always connected in circuit, and under normal conditions only, entail a small loss, yet are sufficient to limit the short-circuit current to a value which can be dealt with by the automatic switches, and also to a value which is not dangerous to the electric generator themselves such as that due to the electro-dynamic forces between the conductors.

of the machines and which results in the windings becoming displaced and, even in the extreme cases, the destruction of the machines. When a short-circuit occurs in a system, the voltage will drop, the amount of drop will depend upon the magnitude of the short-circuit and the inherent characteristics of the generators, *i. e.*, the impedance.

Oil immersed current limiting reactors are similar in appearance to transformers and are used after it is necessary to insulate phases where concrete cells cannot be conveniently installed, or where the uttermost reliability is required making thorough shielding necessary.

Reactor units for circuit protection and improvement of operating condition are often single phase air-cooled type and in groups of three on three phase circuits. Wide clearance, asbestos insulation and one piece of concrete supports make them remarkably trouble free.

Function :—By means of the proper installation of reactors, the whole station, or even several stations may be operated in multiple, while at the same time, the several sections may be protected from each other, and each section from the individual circuits which it feeds. Troubles may be localised or isolated, practically where they originate, without communicating their disturbing effects.

A severe short-circuit, such as may occur when there are no reactors, will cause the voltage to drop to a low value in a few cycles, whereas, on a less severe short-circuit, the time taken for the voltage to drop to the same low value will be longer. Synchronous apparatus will stand a complete loss of power for a few cycles only, but will stand a reduction of voltage for a longer period. It is important then, that the value of short-circuit be small and that it be cleared in the shortest possible time. Introducing reactors will limit the maximum value of the current ; and, with the latest type of relays, the time required for selective switch action is very short, so that, a trouble can be localised and cleared before the apparatus or the rest of the system is affected.

The protective and localising functions of a reactor are, however, quite distinct. The former, since all the evil effects of heavy current, excessive mechanical stresses, heating, etc., are proportional to the square of the current, is measured in terms involving the square of the total reactance, while the latter is measured in terms of the first power of the reactance involved.

The chief purpose of a reactor is, therefore, to limit the flow of current into a short-circuit with a view to protect the apparatus from overheating as well as failure from destructive mechanical forces; also to protect the system as a whole against shut-down, by maintaining the voltage on the part of the system while the short-circuit is being cleared.

The most important *field of application* for the current limiting reactors are (1) when effecting extension of established plant, (2) when sectionalising the bus-bar systems of distant stations into several groups, (3) for the protection of feeders and alternators possessing a low inherent reactance. It is used in synchronous tie-in-type of printing press drives. (4) ingenious use is made in the relay that protects the squirrel cage winding in a synchronous motor from overheating. Double squirrel cage motors designed to give high starting torque, without the excessive slip of high reactance rotors, contain what is virtually built in rotor.

Reactor starting of motor is used to some extent. Some advantages of reactor starting are as follows :—

(1) Low cost with low starting duty. (2) Motor is not disconnected from the line while starting. (3) Reactor does not limit heat as does a resister. (4) Reactor starting calls for only two circuit-breakers, one of which can be comparatively small.

Rating :—Reactors are generally spoken of as introducing a certain per cent. reactance in a circuit. This is the ratio of the voltage drop across the reactor (when the rated current of the circuit at rated frequency is flowing through the reactor), to the voltage between line and neutral on three-phase circuits, or the voltage between

the lines on single-phase circuits. The reactance is, therefore, expressed as being single-phase in either case.

Current-limiting reactors should, furthermore, be designed for the maximum load current they will have to carry. Being self-cooled and having neither iron nor oil to provide thermal storage, they reach their maximum temperature very quickly. Therefore, in cases where the apparatus or circuits must carry overloads for two hours or more, this overload current should be considered the rated current of the reactor, and the capacity should be selected on this basis. Under this assumption, a temperature rise of 80° C represents common practice, the rise being based on an ambient room temperature of 40° C.

As reactors, as a rule, do not have an iron core to become magnetically saturated, the reactive drop will be proportional to the current. That is, if a circuit having a 10 per cent. reactor were to be short-circuited at the reactor terminal on the load side and have full sustained voltage on the supply side, the sustained current would be limited to $100 \div 10$, or ten times normal. It should be remembered that transformers and generators in circuit with the reactor also have definite values of reactance which, when expressed in terms of the current of the circuit (per cent. reactive drop with normal current flowing), may be added directly to the reactance of the reactor to determine the total apparatus reactance of the circuit. This total reactance, plus the reactance of the line upto the point of short-circuit, divided by 100, gives the approximate short-circuit current (the result being expressed in number of times normal).

Care must be exercised, in calculating the possible short-circuit current of a system, that the various per cent. reactances are on the same basis, *i. e.*, on the same current value. For example, if the reactance for a 8,000 K. V. A , three-phase transformer is given as 8 per cent, but a value is required which corresponds to one of the generators, having a capacity of, say, 4,000 K. V. A., three-phase ; the corresponding value would then be

$$\frac{4{,}000}{8{,}000} \times 8 = 4 \text{ per cent.}$$

Similarly, it must also be remembered that reactance values given for single-phase transformers really refer to a bank of three such transformers. For example, the reactance of a 6,000 K. V. A., single-phase transformer is given as 3 per cent. This, then, usually refers to the full-load current from a bank of three such units, *i. e.*, 18,000 K. V. A., so that, if the reactance were to be converted to the basis of a 6,000 K. V. A. generator, its corresponding value would be $\frac{6,000}{18,000} \times 3 = 1$ per cent. A careful consideration of the above is of the greatest importance when reactance values for generators, transformers, and transmission lines of different capacities are to be combined.

Rating as Affected by Frequency :—A reactor designed for a given frequency may be used in a circuit of different frequency, in which case, the per cent. reactance is approximately equal to the ratio of the frequency for which it is to be used to the frequency for which it is designed, times the per cent. reactance for which it is designed.

For Example :—A $3\frac{1}{2}$ per cent. 25-cycle reactor may be used in a 40-cycle circuit, in which case, the per cent. reactance is approximately $\frac{40}{25} \times 3\frac{1}{2} = 5\ 6$ per cent.

Rating as Affected by Voltage :—A standard reactor can be used for lower voltage circuits than those for which it is designed ; in which case, the per cent. reactance is increased in the ratio of the voltage for which it is designed to that for which it is to be used.

For Example :—On an 11,000-volt, three-phase circuit requiring the introduction of about $3\frac{1}{2}$ per cent. reactance, it will be possible to use a 13,200-volt, $3\frac{1}{2}$ per cent. reactor. The reactance will be $3\frac{1}{2} \times \frac{13,200}{11,000} = 4\ 2$ per cent.

Rating as Affected by Current :—A standard reactor may be used for lower currents than that for which it is designed; in which case, the per cent. reactance decreases with the ratio of the current for which it is to be used to the current for which it is designed.

For Example :—A $3\frac{1}{2}$ per cent. 350-amp. reactor may be used in a 300-amp. circuit where it will insert

$$3\tfrac{1}{2} \times \frac{300}{350} = 3 \text{ per cent. reactance.}$$

From the foregoing it is seen that a $3\frac{1}{2}$ per cent, 25-cycle, 13,200-volt, 350-amp. reactor will introduce in a 40-cycle, 11,000-volt, 300-amp. circuit a reactance of

$$\text{approximately } 3\tfrac{1}{2} \times \frac{40}{25} \times \frac{13{,}200}{11{,}000} \times \frac{300}{350} = 5{\cdot}76 \text{ per cent.}$$

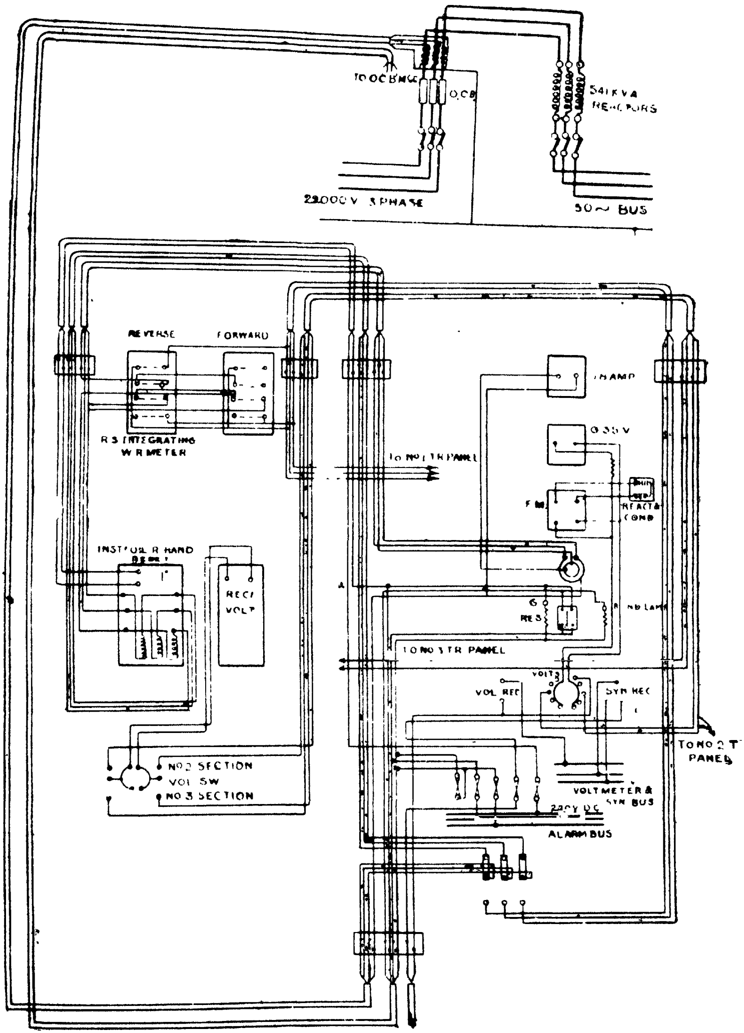
Effect of Reactance on Power-Factor :—Increasing the reactance in the system results only in a slightly lower power-factor.

Effect of Reactance on Regulation :—As in the case of the power-factor, an increase in the reactance results in a slightly poorer regulation, the effect being more marked if the operating power-factor is much below unity.

Losses :—The losses in reactors are not a serious matter, but should, of course, be taken into consideration in laying out the system.

Bus reactors, on the other hand, carry normally very little, if any, current and the losses under normal operations are, therefore, negligible.

Location :—Reactors may be located in the system in such a way that they will not only reduce the mechanical strains due to short-circuit, but will also practically localise its effect to the circuit or section where it occurs. They may thus be placed in the generator leads, between the bus sections, in the low-tension transformer leads or in outgoing low-tension feeders or tie lines. Which one of the above locations or combination there of is preferable, depends upon a number of conditions, each location having its advantages and disadvantages.



Reactor Equipment at Dheravi Receiving Station (Tata).

Fig. 10·43

The diagram of connections of the reactor equipment at Dharari is shown in Fig. 10·43. The Tata power is tied on to the Andhra power through a system of reactors. These are rated at 541 K. V. A. and are of B. T. H. manufacture, cast in concrete and having a resistance of 0·82 ohms. They are designed to carry a current of 812 amperes at 23,100 volts and 50 cycles. The arrangement is such that the reactors are always in circuit when there is exchange of power so that no more than 2,700 K. V. A. can be passed. The drop across reactors is then 66 volts, reactance drop 5 %.

They should not be located close to steel frame-work ; and loose steel or iron parts should be kept away from them. In a heavy short-circuit, great forces are set up between the reactors. Hence, they must be braced well apart. Even if located in separate cells, they should be braced to the walls to guard against side thrust.

605. Generator Reactors :—It necessarily limits the current that can flow into any short-circuit beyond the reactors, in as much as the amount of current which can flow is limited to what the generators can supply. An objection to generator reactors is the fact that a short-circuit on or near the bus-bars will cause a voltage drop on all the lines or feeders connected thereto. If the short-circuit is severe, the voltage may drop to zero, and this, of course, will cause all the synchronous apparatus connected to the system to drop out of step.

606. Transformer and Feeder Reactors :— Reactors in low-tension feeders are very common however, and have many advantages. The probability of a short-circuit in a teeder is far greater than in any other part of the system, and the short-circuit current through a feeder switch may be considerable, since the current from all the generators will pass through the same, and possibly, also the current from other synchronous machines on the system. By means of feeder reactors, however, such troubles may be still more limited than if bus reactors were provided, and it is merely a question of cost whether such reactors can be afforded.

Feeder reactors, of course, only give protection for those short-circuits which occur on the feeders beyond the point where they are installed, and do not give protection to short-circuits which occur on the bus-bars or in the generators, transformers or their connections.

607. Number of Reactors:—The following is considered the best practice for locating reactors in various circuits :—

(*a*) For single-phase circuits, a single reactor in one side of the line.

(*b*) For two-phase, four-wire circuits, two reactors, one in one side of the line of each phase.

(*c*) For two-phase, three-wire circuits, one reactor in each of the outside lines (as distinguished from the neutral or common wire).

(*d*) For three-phase circuits, one reactor in each line.

608. Size of Reactor :—A sharp distinction must, therefore, be made between an instantaneous and a sustained short-circuit, the former being dependent upon the instantaneous effective impedance of the system and the latter on the sustained effective impedance.

The instantaneous short-circuit current is readily calculated, being equal to the normal current multiplied by 100 and divided by the total reactance to the fault, expressed in per cent. For modern water-wheel-driven generators, the inherent reactance varies from 15 to 25 per cent. and for transformers from 6 to 10 per cent. As expressed in per cent. it may be obtained from the formula :—

$$p=\frac{X\times \text{K.V.A.}}{10\times E^2},$$

where $p=$ reactance in per cent. ;
$X=$ single-phase reactance in ohms ;
$E=$ voltage between phases in kilo-volts.

The reactance in ohms per one mile of one wire of a symmetrical three-phase circuit is

$$X=2\pi fL=2\pi f\left(0{\cdot}74\ \log_{10}\frac{s}{r}+0{\cdot}0805\right)10^{-3}$$

in which s=spacing between centres of conductors in inches ;

r=radius of conductors in inches.

609. The principal elements that contribute to the *strength and efficiency of modern* "cast in" reactors are as follows. Finally stranded cables of small diameter keep to a minimum the stray losses within the conductors due to the magnetic field. Parallel sections of winding are used, where necessary, to carry the current and retain this feature. By reason of the special method of winding in these parallel lengths of cable, having the same resistance and the same inductance, extra losses due to unequal division of current are eliminated. As a final finish, the complete reactor is dipped and baked number of times in a fire resisting enamel. This enamel permits the strands of the cable and helps further to reduce the stray losses. Extra spacing of end-turns eliminates danger of flash-over due to high frequency transient voltages at times of disturbance on the system. Fire-proof composition spacers moulded under great pressure form the supporting structure. The slots into which the cables are laid in the winding operation provide sufficient clearance to permit expansion of the copper due to rapid heating at the time of short-circuit. Wooden rods, specially treated, are used to clamp the columns of spacers together. These, being entirely enclosed in the fire-proof spacers, do not form an inflamable element. One terminal is placed at one end of the coil and the other at the other end to eliminate the danger of flashing across terminals.

Example 10.

Alternator No. I — Alternator No. II

X_s=10 % — X_s=12 %

10,000 K.V.A. — 2,300 volts. — 15,000 K.V.A.

Transformer 25,000 K.V.A. X_s=5 %

Reactor X_1

X

Find for the above case, the per cent. feeder reactance to limit the instantaneous symmetrical short-circuit current to four times the normal current when a 3-phase short-circuit occurs at X.

The circuit reactance must be expressed in terms of the total K. V. A. capacity.

Solution—

Equivalent reactance of alternator No. I

$$= \frac{10 \times 25{,}000}{10{,}000} = 25\ \%.$$

Equivalent reactance of alternator, No. II

$$= \frac{12 \times 25{,}000}{15{,}000} = 20\ \%.$$

Combined reactance of the two in parallel,

$$= \frac{1}{1/25 + 1/20} = \frac{20 \times 25}{45} = 11{\cdot}1$$

Total reactance to short-circuit,

$$= 11{\cdot}1 + 5 + X_1 = 16{\cdot}1 + X_1$$

Since % reactance $= \frac{I_1 X}{V}$, I_1 being the rated current of reactance circuit, and since the short-circuit current in the reactance circuit is practically $\frac{V}{X_1}$,

$V = I_2\, X_2 = I_1\, X_1$ per cent. reactance, I_2 being the short-circuit current.

$$\frac{I_1}{I_2} = \tfrac{1}{4} = 25\ \%$$

$\therefore\ X_1 + 16{\cdot}1 = 25$

or $X_1 = 8{\cdot}9\ \%$ at 25,000 K. V. A. capacity.

610. Reactive Volt-ampere Indicators :—

(1) They measure the idle or reactive portion of the power and are the only instruments which do so directly.

(2) In connection with the reading of an indicating wattmeter, the readings of the reactive volt-ampere indicator give an easy means for figuring the power-factor.

(3) They are considered in some cases more valuable than power-factor indicators, since they are given an actual quantitative reading in kilo-volt-amperes, while the power-factor indicator gives a reading in per cent. only. This fact can readily be seen from an inspection of the following simple formula :—

$$\text{Power-factor} = \frac{\text{True watts}}{\text{Apparent watts}},$$

where the apparent watts is the vector sum of the true watts and the reactive watts. The reading of a power-factor indicator gives no actual indication of magnitude of the idle currents which cause heating. For instance, at light load, a power-factor of 0·7 or 0·8 would be no cause for alarm, while at full load or overload, it might mean serious heating due to idle currents. This is especially true on synchronous converters, where, on account of the rectifying action of such machines, the cross-section of copper is made smaller than in a generator of the same capacity.

611. Capacitator :—The economical operation of a generating and distributing system is dependent on the maintenance of a relatively high P. F Central stations recognise, that low P. F. loads cause increase of generation transformers, and distributing feeders, as well as increased heating losses and impared voltage regulation. In many cases, on large generating systems this condition has wanted the installation of a synchronous condenser in the sub-station, or if an attendant is available, at the point of application of the reactive load, to overcome the detrimental effect of a low power-factor load. In order to meet the demand for the condenser, the capacitator has been developed.

The capacitator is an extremely efficient device, the losses in the directly connected equipment being one quarter of one per cent. of the rated K. V. A. capacity. This low loss of the capacitator, its serviceability indoors and outdoors, as both types are available, should be taken into consideration when this type of equipment is compared with other apparatus designed for power-factor correction.

Operation :—No attendant is required to operate a capacitator. It may be on the line indefinitely with only a systematic inspection to see that it is operating satisfactorily. Because of this, the equipment may be installed in any out of the way place or in a sub-station that may be inspected only monthly or even at large intervals. The operation is practically noiseless.

Location :—Since there are no revolving parts, no special foundation is necessary on which to locate the capacitator, other than that necessary to bear its dead weight. The floor space required is small per K. V. A. of capacitator capacity.

When operating at normal capacity continuously, the capacitator section will have a temperature rise not to exceed 10° C. The temperature rise of the coil will not exceed 55° C. The capacity of an equipment is a function of the voltage and frequency, and it is, therefore, impossible to overload a capacitator provided normal voltage and frequency are maintaind.

In order to take care of the voltage fluctuation found in practice, the equipments are designed to operate at voltages ranging 10 % either side of the rated voltage of the equipment. It should be understood however, that the corrective capacity of the equipment will vary directly as the square of applied voltage and also directly with the frequency.

The capacitator has the property of altering the phase relation between E. M. F. and current by a fixed amount. The P. F is practically zero, so that its entire capacity is used to overcome the amount of lagging current.

The connection for 3-phase, 220, 440, or 550-volt capacitator is shown in the Fig. 10'44.

VOLTAGE REGULATORS

612. Tirrill Voltage Regulator:—In power-stations where wide variation of load is constantly occurring, voltage regulation by an automatic regulator becomes a necessity and for this purpose, the tirrill regulator is

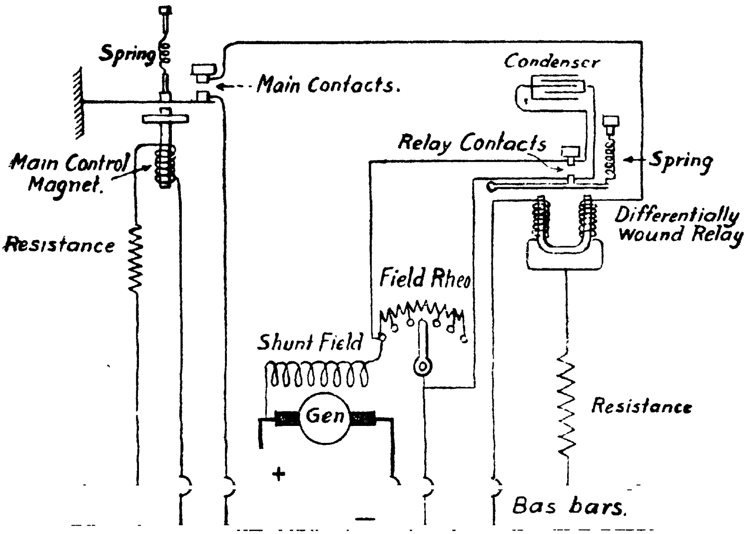
admirably suited. The apparatus is very sensitive and when in commission, can deal equally well with small or large variations in load and incidentally the voltage, so that, regulation by hand is entirely eliminated.

The regulator works in conjunction with the rheostat of the generator by means of solenoids and vibrating contacts. Within the working range of generator, good results are obtained with a regulator designed to suit the characteristics of the particular generator it is to control.

The successful operation of a tirrill voltage regulator largely depends upon the care and attention given during all stages of installation and testing before placing in service. Once properly installed and adjusted, it only requires a reasonable amount of maintenance, consisting chiefly of the replacing of dash-pot oil and periodic inspection, cleaning and adjustment of the relay contacts. A tirrill regulator is essentially an instrument of precision and should be tested as such.

Principle of Operation :—Constant voltage at the generator terminals is obtained by intermittently short-circuiting the exciter field rheostat in such a manner that the exciter voltage is automatically varied to suit the particular conditions of load on the generator. The intermittent short-circuiting of the exciter rheostat is carried out by means of relays, which are controlled by main vibrating contacts, that are in turn, directly controlled by the terminal voltage of the generator.

613. D. C. Voltage Regulator :—The Fig. 10·45 shows the connection diagram for the regulator. The control magnet winding is connected across those points between which it is desired to keep constant voltage, in the case of transmission across a supply mains. On the voltage increasing, the core of the control magnet is pulled down opening the main contacts, which, otherwise, would be kept closed by springs. The relay is differentially wound. One half the winding is connected across the supply mains, the other half is also connected across the supply mains, but its circuit is interrupted at the main contacts. With these latter closed, both halves of the winding of the relay are energised and magnetically-



Tirrill Voltage Regulator for D. C. Generator.
Fig. 10 45

cancel each other ; consequently, the relay contacts are closed and short-circuit the shunt rheostat. The condenser shown across the relay contacts is to prevent sparking at the same.

Regulator for A. C. Generators :—The regulator can be considered to consist of three essential parts.

(1) the direct current control magnet, left-hand top-coil.

(2) the alternating current control magnet, right-hand top-coil.

(3) the relay which is controlled by opening and closing of the main contacts.

If for any reason the generator voltage falls, the current in the A. C. control magnet and hence, the pull exerted by this magnet are correspondingly reduced. This closes the main contacts, which in turn close the relay

contacts, thereby short-circuiting the exciter field coils and causing the generator voltage to rise. If allowed to do so, the generator voltage would ultimately reach the higher value corresponding to maximum excitation voltage. The generator voltage would take an appreciable time to rise to its full value, but it quickly reaches at lower value where it causes sufficient additional current to flow in the A. C. control magnet to produce a pull strong enough to open the main contacts. Simultaneously the relay contacts open, thereby inserting resistance in the circuit of the exciter field, the generator voltage immediately commences to fall towards the lowest point.

Details of Equipment :—The A. C. control magnet coil is supplied from the voltage transformer or it may be connected directly to bus-bars if the voltage does not exceed 660 volts. A soft iron core is suspended below the centre of this coil so that when the latter is energised the core is pulled upwards. The core is attached to the

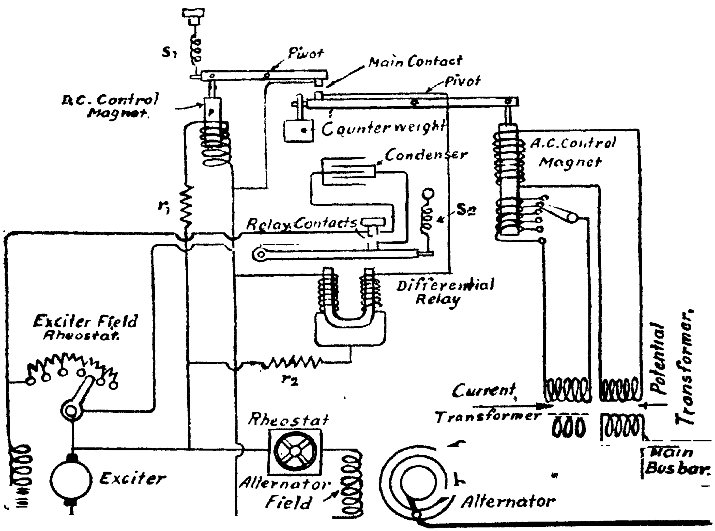


Fig. 10·46

lever by means of the connecting rod and the lever is pivoted at its centre and at the opposite end to the core carries the lower main contact and a counter-weight. The weight of the core is partly balanced by this counter-weight so that, with the coil energised at normal voltage, the lever is balanced. There is a balancing spring used to stabilise the A. C. system and to prevent hunting. It is fixed to the left hand side of the lever and attached to a bracket having an adjusting rod fitted with locking nuts. This rod should be set normally so that, an equal amount of screwed portion extends on each side of the nuts.

The D. C. Control Magnet Coil:—It is energised from the exciter armature. A soft iron core is suspended within this coil and arranged so that it is attracted downwards towards the adjustable core. The adjustable core is secured by a locking screw. Connected to the moving core, is a pivoted lever carrying the top main contact on a spring connection. The top main contact can be locked by a screw. It is important that the moving core should not touch the adjustable core as this will affect the action of the regulator. The movement of the core is controlled by springs which are anchored by a bar, and these springs come into play successively as the pull on the core increases the increasing exciter voltage.

Main Contacts:—The main contacts are fitted to the ends of the vibrating levers. The upper contacts on the left-hand lever is dome shaped and spring mounted. The lower contacts are flat and rigidly fixed to the lever. This arrangement allows a rolling action as the contacts and levers move up and down.

Compounding or Parallel Running Coil:—To enable two or more generators to run in parallel each with its own tirrill regulator, each regulator is provided with a compounding coil which is wound with the coil of the A. C. control magnet. This additional coil is connected to a current transformer usually placed in that place in which the voltage transformer is not connected. The correct position is always shown on the maker's diagram. The object of the compounding coil on each regulator

is to ensure equal division of the wattless current between the various machines. The same type of coil is also used as a compensating coil.

Compensating Coil for the Drop:—When it is required to increase gradually the voltage of a generator as the load increases, in order to keep a constant voltage at a distant point of a system, a compensating coil is made use of. It is identical with that used for parallel running but the only difference is that the current transformer energising this coil is connected to the lagging phase of the two phases between which the voltage transformer is connected.

Fig. 10·46 shows a connection diagram of the various coils on the A. C. control magnet and indicates how compensating or compounding can be adjusted by means of the dial switches, the contacts of which are connected to the various tappings on the coil.

Oil Dash-pot:—The lower end of the core of the A. C. control magnet is fitted with a piston, working in an oil dash-pot into which is secured a sleeve not shown. The piston should move freely, as, any static friction will result in erratic working of the regulator. The normal position of the piston is mid-way between the bottom of the sleeve and pot in it. The damping action of the piston can be varied by screwing the sleeve up or down, thus, altering the amount of space between the end of the sleeve and the bottom of the dash-pot. A thumb-nut is fitted to lock the sleeve after adjustment.

Electrical Damping Circuit or Anti-sparking Device:—This device fitted to each regulator is used for absorbing the small amount of energy released at each breaking of the main contacts. The apparatus consists of a condenser in series with a resistance connected across the contacts. In some cases, a high resistance is shunted across the condensers.

Regulating Rheostat:—Each regulator is provided with regulating rheostat on the back of its panel, so that the regulator can be set to work at a given voltage within its range. The dial plates supplied with the operating hand wheel show the direction of rotation to raise or lower the generator volts.

Resistance Box:—It contains external resistances for all regulator coils. It is mounted on the back of the switch board panel immediately behind the regulator.

Relays:—The number of pairs of relay contacts is a function of the maximum exciter field current and the value of the exciter voltage. The coils for the relay are made up in two sections each section consisting of two coils wound differentially. The connections are such that when the main contacts of the regulator are open, one coil in each section is open-circuited. This condition produces a flux in the magnetic circuit, causing the armature carrying the moving relay contacts to be attracted towards the pole piece, and the contacts separated; when the main contacts of the regulator close, both coils in each section are in circuit, but as they are differentially wound, the flux in the magnetic circuit is reduced to zero, thus releasing the armature and allowing the torsion spring to close the contacts. The relay contacts are made of special hard alloy—"Matrix." The contact surfaces are perfectly flat and they are reground on each occasion of cleaning the regulator.

Relay springs consist of flat torsional strips which are held between two poles and adjusted by rocking on a roller. To increase the tension of the spring, the two front screws are slackened and the two rear screws tightened up and *vice versa.*

In adjusting a regulator, the armature carrying the moving relay contact, is just kept "floating" between the fixed contact and the pole piece at a certain current, to be known from the data sheets despatched with the regulator. A set of contact condensers is mounted on a bracket behind the regulator panel. One of these condensers, connected across the relay contacts, is usually sufficient to reduce the sparking to a negligible degree. In case of excessive sparking, an additional condenser in parallel with the first is put. If the sparking is of a sharp crackling nature, it is probably due to the fact that the condenser is too large and is discharging itself across the relay contacts. In this instant, another condenser is added in series with the first.

Each Tirrill regulator is supplied with an emergency cut-out which disconnects the regulator from the system, should the voltage rise or fall beyond pre-determined limits. It consists of a high and low voltage control relay operating a multipole cut-out.

Adjustment and Commissioning of Tirrill Regulator:—To put a new regulator into commission we proceed as follows:—

Wiring is checked on the back of the panel with the certified connection diagram of the equipment. Then, after fitting the counter-weight taking care not to spill the lead shots which may have been placed within the counter-weight and hooking it, the gap between the relay contacts is checked by means of the gauge supplied. Then the main contacts are checked. These should touch when both the D. C. and A. C. control magnet levers are resting on their respective stops.

Then the dash-pot is fitted up to within $\frac{1}{4}''$ of the top with a good grade turbine oil. The piston is moved up and down by hand to see that it is quite free.

The generator is then run upto normal speed; brought to normal voltage by the exciter shunt field rheostat. The no-load voltage of the exciter is checked with the value given on the Tirrill regulator name plate. Again turn the exciter field rheostat down until generator is giving 10 % of its normal voltage. The position of the rheostat arm is marked. This is known as the "Tirrill position." It is very important to mark this position clearly on the rheostat, for the arm must be brought to this position when the regulator is controlling the generator. With the exciter field rheostat in the Tirrill position, the correct location of the tapping leads to the regulator relay terminals is found out, so that all pairs of relay contacts can be connected across rheostat sections of equal resistance. The regulator relay contacts are connected to operate a sufficient position of the exciter rheostat that will give an exciter voltage 15 % in excess of that required at maximum load, the relay contacts being held closed. First, the exciter is run on open circuit under hand control and the position of the

rheostat arm is noted, that will give 20 % to 25 % excess to allow for the internal drop in the exciter when on load. Now the rheostat is "cut in" to the Tirrill position; and the voltage drop between the "15 % excess voltage position" and the Tirrill position is measured. This voltage drop is divided by the number of pairs of relay contacts on the regulator, the points on the rheostat are successively determined which give a voltage drop corresponding to the result. When these points have been determined and marked on the rheostat, the corresponding leads, according to the connection diagram, are connected to them. The position of the cut-out tapping is then determined. The position of the exciter field rheostat is marked when the generator is under ⅔rds of the normal load and the tapping is taken from the stud on which the arm is resting.

Then the lever of the A. C. control magnet is balanced. The voltage transformer is made alive and the regulating rheostat is placed in central position. By adding or removing lead shots from the counter-weight, a balance is obtained on the lever, so that, if the core is displaced by hand either up or down, it tends to remain in new position. A further test is made by slightly altering the regulating rheostat. The core should move either up or down depending upon the direction in which the rheostat handle is turned. The setting of the balancing spring is not to be interfered with. The lever of the D. C. control magnet is held clear while balancing the A. C. lever.

In order that A. C. control magnet will respond as quickly as possible to changes of voltage, the dash-pot is set with a minimum amount of damping consistent with the stability of operation. The dash-pot is adjusted with the generator running on no-load under Tirrill control and stability tested by cutting the regulating rheostat 'in' and 'out' a few times.

The high and low voltage cut-out tripping values are now set. While setting the cut-out tapping, the exciter rheostat should be dis-connected, otherwise, on the cut-out operating, the generator voltage may rise to an excessive value. A. C. regulating rheostat must be

in the position for putting the regulator into operation at normal generator voltage in order that the impedance of the circuit comprising the A. C. control magnet, regulating rheostat and cut-out control relay will be of the correct value.

The dash-pot on the cut-out control relay must be set with more damping effect than that on the A. C. control magnet in order to give the relay a sufficient time lag to prevent it operating on momentary voltage surges.

The polarity of the compensating coil is tested and phase connections are ascertained. The generator voltage should rise when the coil is switched on.

Operation :—To put a Tirrill regulator in operation on a running machine,

(1) it must be seen that the cut-out control relay switch, that is the single pole switch on the left-hand side of the regulator base is open,

(2) see that the multipole cut-out is set,

(3) close the isolating switch on the regulator panel,

(4) by means of regulating rheostat, balance the arm of the A C. control magnet. See that the relay contacts are just trembling This can be done by a system of 'boacketing' *i. e.*, by turning the rheostat arm in one direction until the relay contacts close and then turning it rapidly in another direction until they open, gradually reducing the amount through which the rheostat is turned.

(5) close the relay-switches at the bottom of the regulator sub-base.

(6) gradually turn the exciter field rheostat down until it is in the 'Tirrill' position The regulator will now control the voltage of the generator throughout the whole range of its load.

(7) then finally the cut-out control switch is closed making certain that the moving contact is mid-way between the two fixed contacts.

How to Put It Out of Operation :—(1) First of all, take off the cut-out control relay switch.

(2) The exciter field rheostat is raised gradually until the relay contacts on the regulator just stop beating. The single pole switches at the bottom of the regulator sub-base are opened. The generator is now out of control of the regulator. Lastly isolating switches are opened up at the bottom of the regulator panel.

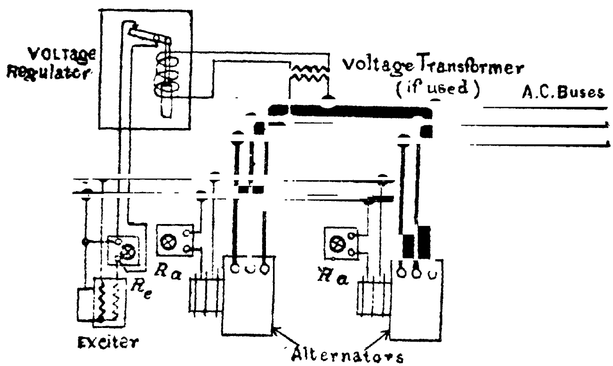
614. A Simple Generator Voltage Regulator.

R_e is the exciter field rheostat,

R_a, R_a are alternator field rheostats.

When the bus voltage is too high, the plunger in the voltage regulator is drawn up and the contact is opened, thus putting the regulator in the exciter rheostat in series with the exciter field. Causing the exciter voltage to drop decreases the exciter field current and thus the voltage of the alternator When the voltage is too low, the plunger in the voltage regulator drops, the contact closes and thus the voltage is raised. The regulation takes place very rapidly and is a most satisfactory method of maintaining a constant voltage.

A Voltage Regulator Relay or contact making voltmeter is similar to voltage regulator as shown in Fig. 10'47.



Generator Voltage Regulator and Connections.
Fig. 10 47

615. Locating Faults:—If the voltage fails on putting regulator into circuit, carefully check up the following points:—

(1) See that the reversing switches are thrown to the extreme position, either up or down.

(2) See that the single pole switches at the bottom of the regulator are closed and make good contacts.

(3) Look for wrong connections and bad connections.

(4) See that the relay contacts are clean and make good contacts.

(5) Note that the relay contacts open and close as the main contacts make and break.

616. Fluctuating Voltage:—If the voltage tends to fluctuate after a regulator is put into service, check over the following points:—

(1) See that the upper main contact is light; if necessary, re-adjust it as described before by means of set screw. The adjustment of the top main contact is very important and should be undertaken with care.

(2) See that there is no undue friction at the pivots, and they are not worn out. See that the pins are good fit in the rods of A. C. and D. C. control magnets respectively.

(3) Note that the regulator is not subjected to excessive vibration.

(4) Note that the dash-pot is actually full of clean oil of correct constituency, and that the valve setting is correct. See that the dash-pot is firmly fixed to its supporting base, that no air is included, and that the piston is moving freely inside the cylinder.

(5) Examine the cores of the D. C. and A, C. control magnets to see that they do not touch the inside of the respective coils.

(6) Carefully inspect all wiring and see that the slip-rings of the exciter are in good condition.

(7) Examine the sparking at the main contacts, the device for which is described under "electrical damping circuit."

(8) Examine the sparking at the relay contacts. This is possible due to incorrect capacity across the condenser. The way of the adjustment is already given before.

(9) See that the relay contacts are clean. If these are inclined to pit, a piece of fine carborandum cloth may occasionally be run between them for superficially cleaning them, the back of the cloth being used to remove any dust that may have remained on the metal. See that new contacts and also contacts that have been cleaned are making superficial contacts and not point contacts.

617. Metropolitan Vickers' Automatic Voltage Regulator :—The Fig. No. 10·48 gives a diagram of connections of a typical Metrovicks Automatic Voltage Regulator.

The regulator, as will be seen, consists of three main parts *i.e.*, (1) the main control coil, (2) the vibrating coil and (3) the relay coil which are connected as follows :—

The Main Control Coil :—This coil is connected across the mains, the pressure of which is to be regulated, either directly in the case of D. C. or low tension A. C circuits, or also through pressure transformers and resistance marked in the figure.

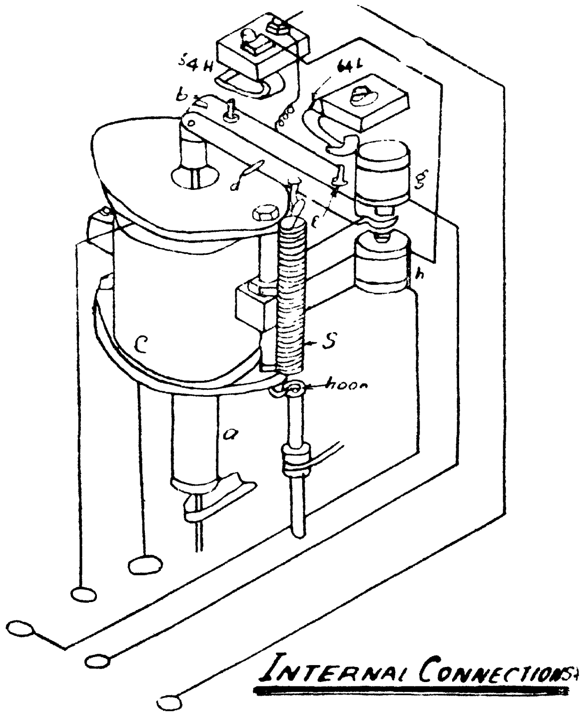
The Vibrating Coil :—This coil is connected up as in the ordinary electric bell, across a 4-volt accumulator and in series with its own contacts so that its armature is caused to vibrate at a given amplitude and frequency.

The Relay Coil :—This coil is connected through 4-pole-switch and through a separate pair of vibrating contacts to the exciter field.

Method of Operation :—Its method of operation is similar to the Tirrill regulator.

617A. Under-Voltage Relay and Voltage-Regulating Relay in one : – This relay is of the solenoid type, the core taking up a position in the solenoid depending upon the voltage of the in-circuit to which the relay is connected.

When used as a low-voltage relay, the falling of the circuit voltage to a pre-determined value causes one set of contacts to close which completes the circuit of a time-delay relay which in turn starts up the automatic equipment.



Voltage Regulating Relay.

Fig. 10'48A.

As a voltage-regulating relay two sets of contacts are employed, one pair 64-L (Fig. 10'48A) being made by a decrease and the other pair 64-H (Fig. 10'48A) by an increase in voltage. Fig. 10'48B shows the actual construction of this relay.

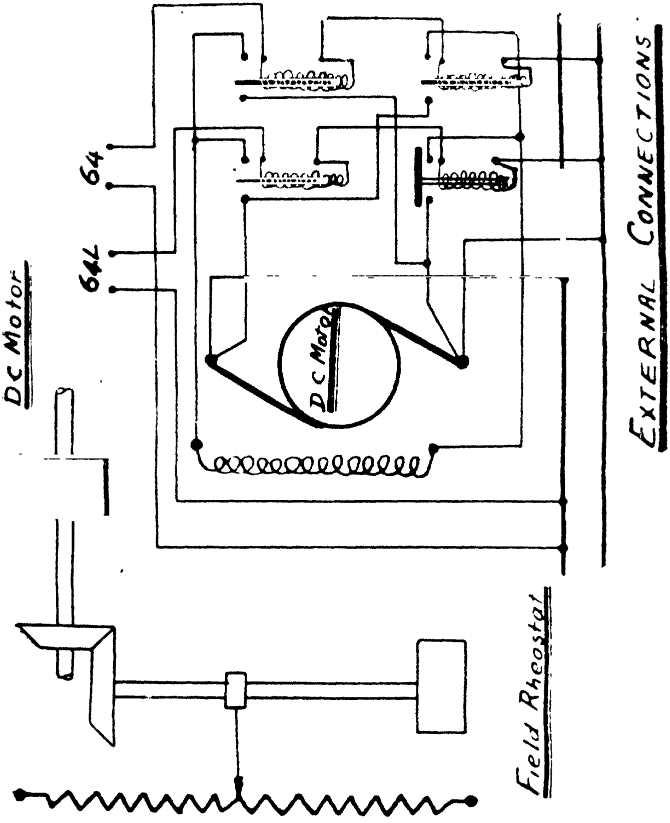
These sets of contacts control the operation of two contactors which determine the direction of rotation of a small motor operating the field-rheostat of the machine being automatically regulated or operated to correct the voltage in some other manner depending on the type of gear being employed.

Construction :—Refer Fig. 10'48A. A core (*a*) is suspended in the coil (*c*) from an arm (*b*) pivoted at (*d*). On the arm (*b*) are carried two contacts (*k*) and (*l*) which operate with fixed contacts 64-H and 64-L respectively. Connected in circuit with these are small electro-magnets (*g*) and (*h*). An adjustment spring (*s*) is attached to the arm (*b*).

Operation :—The coil (*c*) is connected in series with an external resistance to the circuit to be controlled. A fall in the voltage causes the core (*a*) to take up a lower position in the solenoid with the result that contacts 64-L are made, which causes certain apparatus to function as outlined above Similarly with a rise of voltage, the contacts 64-H are made. In the case of the low-voltage relay these contacts are not used.

Chattering of the contacts is prevented by the action of the small restraining coils (*g*) and (*h*). These are connected to the contacts 64-H and 64-L and become energised when their respective contacts close. The magnetic effect of the energised coil on the arm (*b*) is such that the contact remains closed until the voltage becomes normal, or some pre-determined percentage above the normal.

Inspection and Adjustment :—(1) Examine the contacts and clean them if necessary. (2) The arm (*b*) should be free in its bearings and the core (*a*) move freely in the solenoid (*c*). The relays are generally set for a variation of plus or minus 1%; this sensitiveness may be altered by adjusting the gaps of contacts 64-H and 64-L.



Voltage Regulating Relay.
Fig 10'48B.

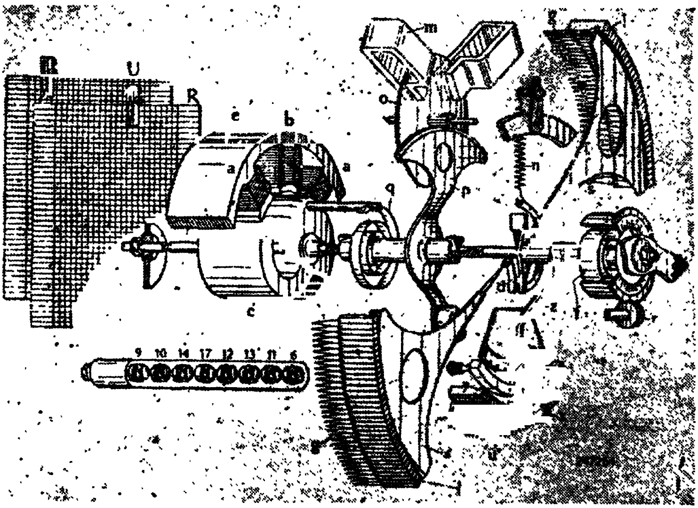
(3) The tension of the spring (*s*) should be such that the contacts (*k*) and (*l*) on arm (*b*) are equidistant from the contacts 64-H and 64-L at normal voltage. Provision is provided for adjusting the spring (*s*).

(4) When the relay is fitted with a compound winding an adjustable resistance is provided to vary the range of compounding.

With maximum movement of moving contacts, the arm (*b*) must not touch the core of the restraining coils (*g*) and (*h*), the position of the latter to be adjusted so that the relay will break contact with the required percentage more or less than the voltage which just causes the contacts to be made. The adjustment of the position of these restraining coils is effected by means of the thumb-nut and lock-nut on the screwed rod which carries the coil.

The spring supports of the contacts 64-H and 64-L should be set clear off the reinforcing piece so that pressure of the contacts (*k*) and (*l*) will produce a slight deflection, thus ensuring a wiping action.

618. The Brown Boveri Automatic Voltage Regulator :—



Component Parts of the Brown Boveri Automatic Voltage Regulator.

Fig. 10·49

(*a*) Main winding.
(*b*) Auxiliary winding.
(*c*) Drum.
(*d*) Stator spring
(*e*) Field system
(*f*) Main spring.
(*g*) Resistance elements.
(*I*) Contact tracks.
(*m*) Damping magnet
(*n*) Auxiliary spring.
(*o*) Damping disc.
(*p*) Recall segment.
(*q*) Recall spring.
(*r*) Adjusting screw.
(*R*) Auxiliary resister.
(*s*) Control sectors.
(*U*) Main resister.
(*ú*) Adjusting resister.
(*x*) Sliding contact.
(*z*) Pointer.

Construction :—The motive system produces the necessary torque for the regulation. It consists of the laminated core (*e*) carrying the main coil (*a*) and auxiliary coil (*b*) and the aluminium drum (*c*).

The auxiliary resistance (R) with auxiliary winding (b) forming an auxiliary phase produces a rotating field, the main resistance (U) and the adjusting resistance ($\acute{u}$) being in series with the whole winding system connected across the alternator pressure Fig. 10·50. The torque of the drum on the spindle is proportional to the square of this pressure and is taken up by the main spring (f) and the supplementary spring (n). The free angle of deflection is limited to 60° With the adjusting screw (r), the tension of the main spring can be set for a given pressure.

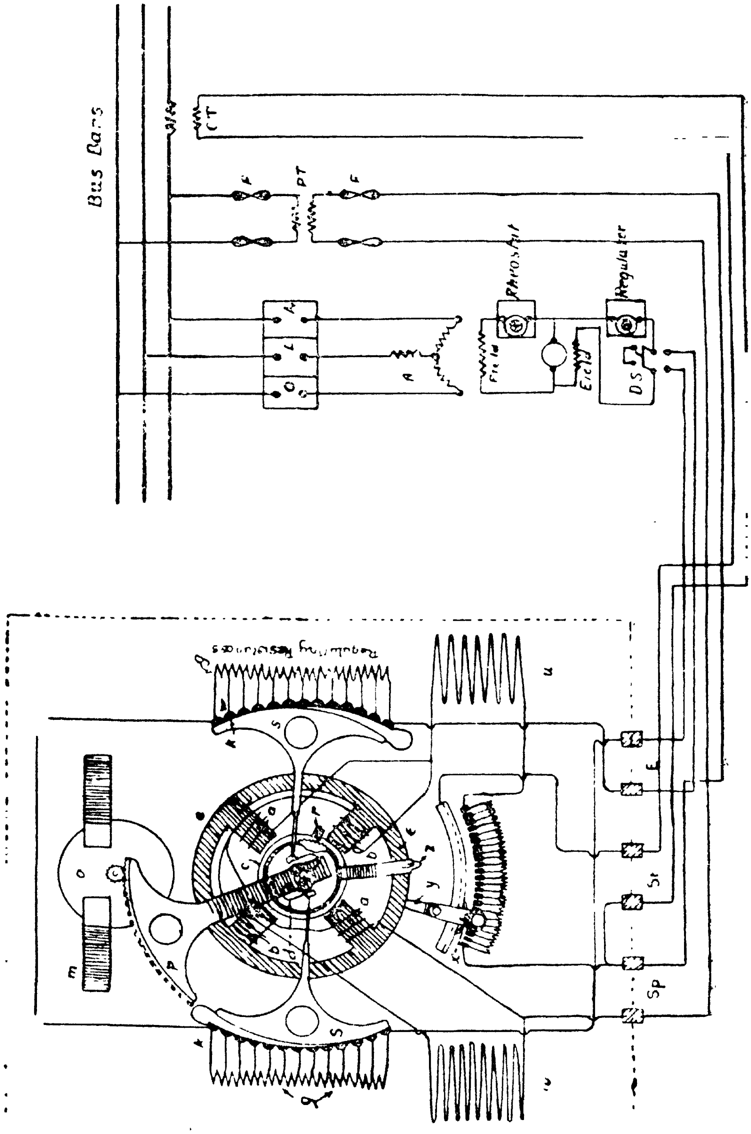
The adjusting resistance ($\acute{u}$) and the sliding contact (x) are used for compounding the regulated pressure in proportion to the load current of the line by means of a current transformer.

The spindle of the drum and the damping disc (p) are coupled flexibly by the recoil spring (q), the damping disc (o) rotating between the poles of the damping magnets (m).

The Regulating Resistance :—The regulating resistance consists of the resistance elements (g) distributed over the contact (I) ; and the contact sectors (s) rolling in the grooves of the contact (I) and pressed against them by the springs (d) with every movement of the drum, the points of the contact sectors are describing an arc of a circle. By this movement of the contact sectors, the point of contact is displaced from segment to segment, inserting or disconnecting resistance elements

Operation :—With the alternator on no-load or a small load only, most of the resistance elements are inserted in the circuit as only a reduced exciter tension is required. The pointer (z) is then near the left-hand stop on the numbers 2—4 of the scale. With the increasing load, the line pressure shows a tendency of decrease ; the torque of the spring overcomes the electro-magnetic torque and drives the drum in a counter-clockwise direction until the contact sectors have disconnected enough resistance to permit the increasing exciter tension to restore the alternator pressure to the desired value.

With the generator on full load, most of the resistance elements will be disconnected, the pointer (z) of the drum


Bus Bars
CT
PT
Rheostat
Regulator
Field
DS
Regulating Resistances
Sr
Sp

being near the right-hand stop ; the exciter tension then reaches a correspondingly increased value. (The pointer (z) on the (0-1) of the scale.)

In case the regulation has to be performed in such a manner that a higher load on the alternator or line corresponds to the higher pressure, a current transformer influences the pressure drop across the terminals 12 and 13 of the adjusting resistance (a) increasing the regulated pressure correspondingly.

The current transformer for the compounding is to be inserted in the lagging phases of the two conductors (R & S) connected with the potential transformer. The current transformer can be used at the same time for the pressure regulator, relays and ammeters, but not without further examination for watt-meters, and phase-meters.

Great care is to be taken concerning the polarity of the terminals 14 & 17.

619. Working Instructions :—

Abnormal Occurrences :—

(a) Permanent deviation from the normal pressure may occur with automatic regulation if the field rheostats are not set correctly ; therefore, the pointer (z) reaches its end position too early. At this moment, the automatic regulation ceases. The adjustment of the field rheostat must be then corrected.

If the operator fails to find positions of the field rheostat whereby the pressure regulator can sufficiently influence the excitation from no-load to full-load, then the regulating resistance is most likely to be small and the shunt field current must be measured.

(b) Hunting may occur owing to the magnetic properties of certain machines. This, in most cases, may be prevented by displacing the damping magnets (m).

(c) In other cases, the value of the resistance elements (g) is too high, that is to say, the displacement of the contacts has a too strong regulating effect.

Observe the position of the pointer (z) at no-load conditions and when operating under normal load conditions. If these two positions embrace less than half the width of the total contact way, the regulating resistance is to be diminished.

With regulating resistances exceeding 10 ohms, the rows of contacts are in most cases in series connections. The resistance can be diminished by short-circuiting a row of contacts or by switching two rows in parallel.

The value of the resistance in ohms is marked on the name plate and refers not to a single row contacts only, but to the total value of the 2 or 4 rows according to the apparatus. The same remark applies also to the two current values, the first relates to the carrying capacity of the steps with short wire (point on 0), the second to that of the step with fine wire (pointer on number 4).

(*d*) The speed regulator of the driving machine and the pressure regulator may mutually cause each other to hunt continuously if the speed regulator works irregularly. The latter must then be improved or else be more efficiently damped.

(*e*) With exciter having interpoles, hunting can be prevented by displacing the brushes from the neutral zone in the direction opposite to that of rotation. But the brushes have to be displaced only to such an extent as is possible without producing sparking at the collector. The behaviour of collector and brushes must to this effect be observed at intervals during several days.

(*f*) Should sparking occur in the rolling contacts it will be necessary to change over to hand regulation. The cause of the sparking may be due either to dust deposits or over-loading of the contacts.

(*g*) When making enquiries regarding abnormal phenomenon, always give the number of the regulator and enclose a completed copy of the test results, the values being taken with the alternator running light and the series and shunt rheostats on definite settings.

The point (z) must be moved by hand from one position to the next. The settings of the series and shunt field rheostats during the tests must be stated.

620. Setting the Regulator to work :—

Mechanical Inspection :—

(*a*) Set the damping quadrant (*p*) free by loosening it from the stop.

(*b*) Ascertain by turning the drum (*c*) if the contact-sectors roll correctly in the grooves of the radial contact (*I*).

(*c*) In the event of the dust having deposited in the contacts, the contact-sectors have first to be taken off by loosening the terminal of the flexible connection and press-sector against the centre, and then by unlocking suspending spring. Then clean the dust.

(*d*) Move the sliding contact (*x*) to its right-hand end position.

(*e*) Look for possible obstructions by removing the point (*z*) to and fro by jerks. The toothed segment (*p*) should follow this motion in a uniform movement as quickly as the eddy current damping allows, and should always stop over the pointer (*z*).

Electrical Inspection :—

(*f*) Connect the terminals 6 and 11 to the corresponding leads of the pressure circuit to be regulated and put in the fuses of the pressure transformer.

(*g*) Adjust the excitation to the normal terminal voltage of the three-phase generator by turning the adjusting screw (*r*) until the drum balances freely.

(*h*) A pressure variation of $\frac{1}{2}$—1 °/o should be sufficient to bring the drum into one end position.

(*i*) Automatic regulation should first be tried, if possible when the generator runs without load, and is prepared by decreasing somewhat the pressure of the generator, whereby the moving system goes to its right-hand end position (number (0) of the scale) short-circuiting the whole regulating resistance.

(*j*) The main field rheostat is to be short-circuited step by step and also the shunt rheostat to such an extent,

that, when the pointer (z) of the pressure regulator, having meanwhile moved automatically from the right-hand stop, is brought back by hand to said-stop, the exciter current is about 1·8—2·2 times the original value.

The momentary excess voltage generated during this manipulation has no harmful consequences if the disconnecting switches to the bus-bars are open. Finally, the drum is again allowed to go free.

(k) The adjustment of the main spring and of the shunt field rheostat, determined in the manner just described, is to be marked and must not be changed. The remaining steps of the rheostat stay inserted in order to avoid an excessive excitation of the generator in case of a short-circuit.

The range of regulation obtained in such a manner should be sufficient to compensate for the variations in the pressure occurring normally.

(l) *The damping of the pressure regulator is tested in the following manner* :—With the generator on no-load, the pointer (z) of the motive system is shifted by hand until the pressure of the generator shows a variation of about 10 %, then it is left to itself. The drum has to perform not more than 2-3 oscillations until it comes to rest and the normal pressure is re-established. In most cases, only a part of the maximum value of damping is necessary and the damping magnets (m) can be slightly separated to diminish the damping effect.

(m) *The adjusting* of the pressure regulator for another value is achieved by turning the adjusting screw (r). Variations in the pressure are admissible upto 6 % without prejudice to an accurate regulation.

Variations exceeding these limits may entail inaccuracies in the regulation which can be met by inserting a special adjusting rheostat in the connection to terminal 6.

(n) " *Changing over to Hand Regulation* " can take place during service without pressure variations. In the first instance, the main field rheostat is to be switched to that position which corresponds to hand regulation.

Then the shunt rheostat is to be inserted until the pointer (z) has reached the stop at the right-hand side. At last the exciter change over switch is switched into position —" Hand Regulation."

(o) *Compounding* :—In order to compensate the pressure drop in an out-going line, the current transformer is connected in phases and to the regulator terminals 12 & 13. The influence which the current of the feeder exerts on the pressure regulation depends on the position of the sliding contact (x). There is no influence in the right-hand end position. By displacing the contact towards the left, the pressure can be made to increase upto 15 °/o above the no-load value under normal conditions of the power-factor and full-load of the line.

(p) If under the influence of compounding transformer by shifting the sliding contact (x), there is a decrease of pressure instead of an increase, the connections to the terminal 12 & 13 or 6 & 11 must be changed. The changing is to be performed only with the generator on no-load, because of the dangerous pressure occurring with the open current transformers. If there is an earth connection on the current transformer, then one has to observe that in changing the connections, the earth connection is always to be made on that terminal of the current transformer which is connected with terminal 13 of the pressure regulator.

(q) It is absolutely necessary before opening the casing, to remove any deposit of dust on the same, and to close again the glass cover of the pressure regulator immediately after each examination, so that, no dust may enter.

Should, after a certain period, dust gather also in the interior of the pressure regulator, it will be necessary to change over to hand-regulation, then to blow out carefully the casing, and if required, to clean the contacts and sectors with a clean dry duster and to remove any residue.

Emery Cloth or Similar Products must not be used on any account.

621. Induction Regulators :—

Induction regulators are rapidly growing into prominence as an effective means of accomplishing voltage control on account of the following advantages :—

(1) Perfectly smooth voltage variation is obtained.

(2) Remote control or automatic operation can be easily applied.

(3) No switches are required in the main supply circuit.

(4) The construction is both simple and robust.

The English Electric Co., has developed designs of induction regulators, which incorporate the results of the most modern research and aim at a high standard of reliability with the least possible supervision. The regulators are usually oil-immersed and either self-cooled or water-cooled.

The maximum line pressure for which these regulators are normally built is 11,000 volts. Above this pressure it is usually preferable to connect the regulator to line by means of transformers and by employing the English Electric Co's double range principle, the increase in cost due to the inclusion of transformers is relatively small. It is a transformer with variable ratio of transformation.

The general construction of an induction regulator closely resembles that of an induction motor, but the rotor is held stationary in a position which can be adjusted by suitable mechanism operated by worm and wheel worked by hand or power. The primary or exciting windings are connected across the supply, and the secondary windings are in series with the circuit to be regulated.

Fundamentally it is immaterial as to which winding is on the stator and which on the rotor. But in induction regulators of English Electric Co 's manufacture, the secondary winding is usually placed on the stator. This arrangement has the great advantage that the secondary winding and leads which carry the heavier current are rigidly fixed and the movable windings and leads are confined to the primary circuit in which the current is

relatively small. Induction regulators above 100 K.V.A. are wound in a four pole arrangement and require a mechanical movement of 90° to give full voltage variation in the normal type and 180° for the double range type.

In the 3-phase regulator, the primary winding generates a rotating field as in the case of an induction motor, and therefore, the magnitude of the current induced in the secondary winding is unaffected by the alteration of position of rotor. Movement of the rotor, however, varies the phase relation of the induced voltage to the primary voltage, and regulator secondary voltage also varies and thereby the required regulation is affected.

In the extreme positions of the rotor, the secondary voltage is respectively in conjunction with and opposition to the line voltage, and the resultant voltage has its maximum and minimum values. For intermediate positions of the rotor, the secondary voltage is out of phase with the line voltage, and consequently, the resultant voltage has a phase displacement relative to the supply. On a simple feeder, this is of no consequence but on a ring main system, or where the L. V. sides of transformers on two feeders are interconnected, this phase displacement may cause heavy wattless currents to circulate. To avoid this defect, it is necessary to adopt either a turn three-phase regulator or a bank of 3 single-phase regulators. The turn regulator consists of duplicate 3-phase regulators simultaneously operated each of half the required K V.A., and with their secondary windings connected in series in such a manner that the phase shift of one is neutralised by the phase shift of the other. This is shown in the Fig. 10·51.

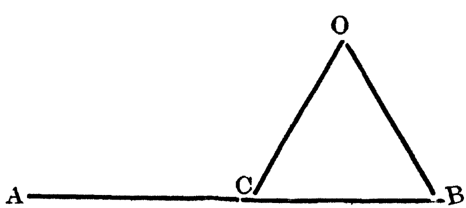


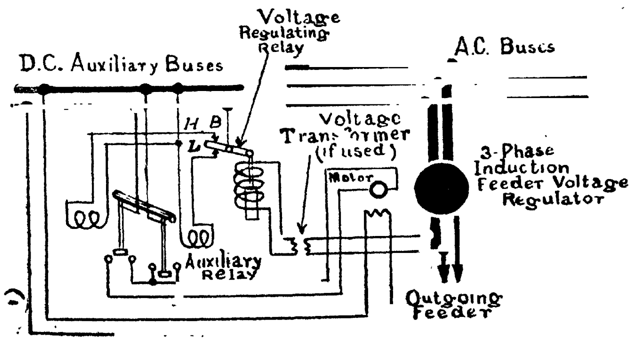
Fig. 10·51

AC=the line voltage.

AB=the regulated voltage.

CO and BO are secondary voltages of the twin halves of the regulator. AC and AB are now in phase for all positions of the regulator.

In single-phase regulators, the secondary voltage is proportional to the alternating flux which threads the winding and is therefore reduced from maximum to zero, as the rotor is turned from full boost position to neutral. If the movement is continued, the direction of the flux relative to the secondary winding changes, and the phase of the secondary voltage is reversed. A complete angular movement of the rotor through one pole pitch, will therefore give full positive and negative ranges of regulation without any phase shift, when the rotor is in the neutral position, the secondary and primary windings are not mutually inductive and the secondary would act as a choke tending to saturate the cores. To avoid this, an auxiliary short-circuited winding is provided on the primary and arranged electrically at right angles to the main primary winding. This additional winding, if properly proportioned, does not increase the losses in the regulator.



Induction Feeder Voltage Regulator.

Fig. 10·52

Certain outstanding features in the design of these regulators may be mentioned here. Special arrangements have been made to direct the flow of cooling oil to the various parts of the regulator, in a measure proportional to the heat production in them. Substantial tooth supports are provided at the ends of the core to hold the teeth rigid, and minimise vibration. Suitable ducts are provided in the rotor core for oil circulation. Both the stator and the rotor windings are designed for operation on line voltage where transformers are not interposed and are insulated to withstand the severe shocks met with in high voltage feeders. The secondary or series winding is almost always on the stationary portion as is of the basket type in open slots. The portions outside the slots are supported to withstand high short-circuited stresses by means of substantial rings in a similar manner to that adopted on large turbo-alternators.

The slot portion of the insulation consists of specially treated paper, machine wrapped and hot pressed, to form solid moulded tubes. No material, which will dissolve in or discolour the hot oil, is used for insulation or impregnation; and the materials chosen are not liable to deteriorate by the action of the oil. Special open-type slots are used for the secondary windings and semi-closed slots for the primary winding. The combination allows a mathematically correct adjustment of slot opening, so that the magnetic permeance remains uniform for all positions of rotor, and thereby smooths the voltage regulating curves and practically eliminates tooth cogging and vibration. The above mentioned features of design are specially met with in the English Electric Co 's induction regulators and they have given extreme satisfaction in service as well.

Although induction regulators are sometimes required for regulation by hand, the more usual arrangement is to provide motor driven operating gear, and the necessary accessory apparatus for either remote control from a switch-board or fully automatic operation. The motor driven mechanism for adjusting the position of the rotor consists of double-reduction work and quadrant gearing fitted with ball thrust bearings on each shaft. The gear

reduction is such as to give a suitable time for complete travel of the quadrant according to the size of the regulator, and the gearing is designed to give the best efficiency consistent with retaining the self-locking properties of work reduction. The worms, worm shaft and quadrants are proportional to withstand the heavy twisting stress which occurs on short-circuit.

By careful selection of the gear ratios and by selecting a slow speed motor, less power is taken from the line for operation, and where D. C. is available, a series motor may be used and switched directly on to the line without protective resistances. For remote control, a small controller is supplied for switch-board mounting with spring return to the "off" postion. To prevent the motor from operating the regulator beyond the allowable limits, two quick-make, quick-break, self-resetting limit switches are fitted, and in addition, safety stops are cast on the cover at each end of the full travel of the quadrant.

As it is important that the motor should stop immediately the supply to it is switched off, the motor shaft is fitted with a break drum on which works a spring loaded brake with self-adjusting Ferrode-lined shoes. In the smaller sizes, the break is permanently adjusted to ensure quick stopping and the motor is made large enough to overcome the brake friction. For sizes above 200 K. V. A., the brake is released magnetically when the motor is switched on but comes into operation immediately the motor circuit is opened.

For emergency use, a hand-wheel or crank is usually provided. When a magnetically released brake is fitted, a foot-lever is added for releasing the brake pressure when it is desired to use the hand wheel. When induction regulators are used as feeder boosters and particularly where the feeder has to supply a mixed load, it is frequently necessary to maintain by some automatic device a constant voltage at the remote end of the feeder irrespective of the load. For this purpose, induction regulators can be fitted with a sensitive type of relay, which controls the operating motor through a pair of interlocked double pole reversing contactors. As the

voltage rises or falls, this relay causes one or other of the contactors to close, thus allowing the motor to adjust the position of the rotor and restore the line voltage to its pre-determined normal value. If the load is mainly lighting or otherwise in the neighbourhood of unity power-factor, reverse compounded series turns on the solenoid of the relay alter the basis voltage according to the load. If, on the other hand, the load is of a mixed nature and the P. F. differs appreciably from unity, it is necessary to include a *line-drop compensator* which incorporates both resistance and reactance and reproduces the line-drop characteristic of the feeder.

The relay is specially designed to make a firm contact as critical voltage is reached and is fitted with no-volt coil so that the regulator is returned to the minimum volts position, if the voltage fails. To prevent unnecessarily frequent operation of voltage, adjustable time delay contacts are supplied which energise the contactors, only after a suitable time interval.

The double range induction regulator of which mention has already been made, consists of an induction regulator with 1·1 ratio between rotor and stator winding. Both windings are in series with the line, and voltage is applied to one member from a transformer. Each winding is therefore half the K. V. A. of the total regulation required. This arrangement is particularly advantageous for comparatively small outputs at high voltage. Taking for example, a 11,000-volt line, having a full-load of 1,200 K. V. A. of which a voltage regulation of 10 % is required, the full-load current per phase would be 63 amperes. In a single three-phase regulator, the primary would have to be wound for a current of 7·5 amperes and would require 60 conductors per slot. A winding of this description being extremely difficult, so that it will stand the mechanical and electrical stresses to which it will be subjected in service, the double range regulator, in which both windings carry the full line current, would be in such a case a thoroughly satisfactory and robust apparatus. The inclusion of a transformer is also compensated for by the reduced size of the regulator, so that neither cost nor efficiency is appreciably affected.

The movement of the regulator rotor through one pole pitch gives a range from full boost to zero boost while a further travel of one pole pitch gives a range from zero to maximum negative boost. The change over of connections is accomplished automatically by the travel of the rotor and entails no special operation. Moreover, this change is made at zero voltage across the regulator when there is only the exciting current of the transformer to break.

For pressures above 11,000 volts, the arrangement of the regulator is modified by interposing a series transformer between the regulator and the line; in which case, the regulator is in an independent circuit, and the winding can be designed for any suitable voltage irrespective of line voltage. This arrangement is also used for split phase conductors, requiring voltage regulation in which case a common regulating transformer and common series transformer are used for both conductor circuits.

The two principal uses of the induction voltage regulator, as described, are as feeder-boosters and in interconnected circuits.

All transmission of electric power is accompanied by losses which manifest themselves as a drop of pressure along the transmission system, and the magnitude of the losses and pressure drop varies with the load and P. F. Apart from rules and regulations as to permissible departure from the declared voltage, this variation of pressure is quite undesirable, at any rate, beyond certain limits, depending upon the class of load served; where the load consists mainly of motors, a certain fluctuation of pressure is not liable to criticism, although induction motors show an increased slip with reduced voltage, and the overload capacity is reduced as the voltage squared.

On the other hand, the increased application of electrical energy for heating purposes and for various electrochemical processes, calls for a closer regulation of pressure, while lighting demands the greatest possible uniformity of pressure. By introducing an induction regulator at one or more points on a system, it is possible to compensate for the pressure drop due to lower power-factor and

I^2R losses ; and in many cases investigation of the financial factors show that the desired regulation can be obtained more cheaply in this way than by increasing the section of copper used for the line; or conversely, a larger load can be carried economically by an existing line without exceeding the desirable limits of pressure variation. The capital charges of the induction regulator together with its running charges and those for the increased line losses will often be found to be less than the capital charges due to an increased copper section in the line.

Induction regulators for feeder voltage control may be placed either at the supply end or at the consumers' end of the line. If at the consumers' end, then the exciting current of the regulator has to be transmitted and supervision is usually easier at the supply end. The best position is usually at a distributing sub-station, where the drop on the line from the generating station to the sub-station and also the drop on the distributing feeder can both be compensated for.

When two power-stations are coupled together through an interconnector, an induction regulator may be used to control the distribution of energy between the lines. The action of the regulator in this instance is quite different as the circuit on which it is operating connects in parallel two sets of alternators.

Induction regulators form the ideal method of voltage control on rotary converters where the range required is greater than can be obtained economically by reactance control, where unity power-factor is required over a range of voltage or where voltage regulation is required in conjunction with inverted running.

These regulators are also a valuable method of voltage control for testing sets, for cable testing and for oil testing sets.

622. Synchronous Condenser Regulation :— The question of regulation of large high voltage systems, involves a number of problems not occurring in low voltage work. In the latter case, the energy loss can often be improved by installing large conductors, which at the same time, will reduce the line loss with high voltage systems, the gain of doing so is very slight and other

means must be resorted to for keeping the regulation within commercial limits. The effect of the inductance and capacitance of the line causes the voltage to vary within wide limits from full-load to no-load. At no-load, the large capacity currents cause a rise of voltage from the generating station to the receiving end while at full-load, the lagging inductive current taken by the load, in general, more than offsets the effect of the capacity current and causes a drop of voltage. It is evident then that, by installing a synchronous condenser at the receiving end and by taking advantage of the characteristics of the machine, the receiving voltage can be kept constant at a determined value or approximately so by adjusting the synchronous condenser field and thus by varying the power-factor causing a lagging current from the line at no-load and a leading current at full-load

The automatic regulation of the condenser field current is readily accomplished by means of a Tirrill regulator. In this instance, the regulator does not hold a constant P. F. but by varying the same, holds a constant A. C. voltage provided there is the proper capacity in the synchronous condenser upon which it is operating. The regulator just endeavours to withhold just as much leading current upon the condenser as there is leading current upon the main transmission line, or else it will endeavour to hold the proper lagging current to counteract the effect of any leading current that exists on the transmission system. The connections and adjustments of the regulator are the same in this case as when used on an A C. generator. In a system of this nature if the synchronous condenser has not ample capacity, there is a danger of burning out of the field due to the fact, that the regulator is trying to maintain constant voltage on the system. It is very important therefore that the highest safe voltage at which to operate the condenser field be determined and the regulator adjusted for this limiting value, which may be 135 volts for a 125-volt excitation. The regulator cannot then hold a higher voltage than 135 ; and, should the voltage reach this value and tend to go higher, the regulator would maintain a constant exciter voltage of 135, but the A. C. voltage would necessarily

drop owing to the fact, that it would be requiring a higher exciter voltage than this valne, in order to maintain the A. C. voltage for which the regulator might be adjusted.

623. Line-Drop Compensator :—

The problem of maintaining a constant voltage at the centres of distribution should be the first consideration of every installation. Specially where power is to be distributed to long distances from a central station, there should be a satisfactory method to regulate the voltage and compensate the line-drop.

The compensator has got two dials as shown in the diagram, marked X and R. X indicating reactance while the other, R, indicating non-inductive resistance. The connection of the current and potential transformers to be used in connection with the current is fully shown in the attached diagram of the regulator together with the line-drop compensator. Over the dials, marked X and R, are two levers which can be swung to cut in and out any amount of resistance, and reactance, and will compensate perfectly for line-drop regardless of variations of power-factors The positions of the levers on the dials are found actually by test, and once they are adjusted to compensate for line-drop from no-load to full-load to maintain the desired voltage at the centre of distribution, no further adjustments are made except under special cases.

The voltage at the generating station is adjusted to get the desired voltage at the centre of distribution, under absolutely no-load condition. Then, with the compensator arms upon the zero point of the dial, the regulator is so adjusted as to give the above voltage by means of proper amount of shot in the shot-cup and by the adjustment of the springs. Those adjustments being made are never meddled with any more while setting the compensator. A recording voltmeter is connected to the system at the centre of distribution and an assistant is appinted there, who is always in telephone communication with the operator who is to adjust the compensator at the central station.

For a particular value of line-drop, there are only limited combinations of resistance and reactance, that can be obtained on the compensator to give the required correct value These combinations being from :—

Maximum resistance to zero reactance.
Maximum reactance to zero resistance.

The resistance lever *R* being placed upon the first point of the dial, the reactance lever *X* is moved to a point that gives correct voltage at the centre of distribution. The resistance lever is now placed on the 2nd stud and the reactance lever is again moved to a point that will give the correct voltage at the centre of distribution. This operation is repeated until all the points on the resistance dial are used and the settings are carefully recorded. The above settings are made at a time when the load is fairly constant, and at the lowest power-factor time of the day.

The above procedure is again repeated at a time when the load conditions are light and when the power-factor is high. By comparing the two sets of reading, an approximate combination of *R* and *X* is chosen to give the correct desired voltage at the place required.

But, when the load and power-factor conditions do not remain steady enough, a cut and try method is adopted to obtain satisfactory compensation. Having made the primary adjustments on the regulator, the resistance and the reactance arms of the compensator are moved to respective points upon the compensator dial that will give the correct voltage at the centre of distribution. In making this setting, both resistance arm *R* and the reactance arm *X* are made to cut approximately equal amounts of resistance and reactance. This setting is left in this particular position for a sufficient length of time to obtain a chart on the recording voltmeter at the centre of distribution with the records of the station load, voltage and power-factor.

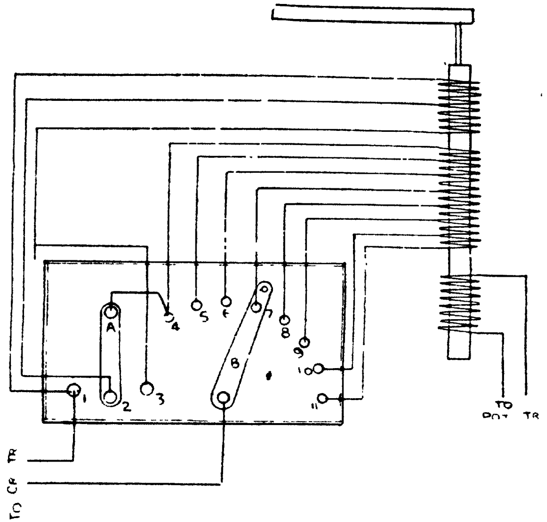
It has been found that the voltage at the centre of distribution goes down under low power-factor conditions ; it indicates that there is not enough reactance and too much resistance is used in the adjustment. In such

cases a new ratio is to be determined upon the compensator cutting in little more reactance and a little less of resistance until the correct voltage is again obtained at the centre of distribution. These adjustments and trials are made until a point is found upon the reactance and the resistance sides of the compensators that will give the correct voltage at the centre of distribution under all conditions of load and power-factor. If the voltage at the centre of distribution goes up upon a decrease in power-factor it indicates that too much reactance and no resistance is being used, and therefore less reactance and more resistance is used to get the desired voltage at the centre of distribution.

By such various trials, the compensator can be set to give a satisfactory voltage in the receiving station, without which it is impossible to maintain a constant voltage.

A second method of line-drop compensation is adopted only during nights after 6 P M. when there is much of non-inductive load (mainly lighting load only). This compensating device is a part of the Tirrill voltage regulator for the generators (frequency changers).

The compensation is accomplished by a single current transformer which has its secondary connected to an adjustable compensating winding on the A. C. control magnet. This transformer is connected in the main lighting feeder leads to which the potential transformer is connected; for with three-phase currents, if the current transformer is not connected to one of the leads to which the potential transformer is connected, it is quite obvious that at unity power-factor, the current in the potential winding will be displaced by an angle of 90° from that in the current winding, and as a result, no compensating effect whatever will be obtained; although in cases where the power-factor is below unity, there would be a slight compensation due to the lagging current. *The arrangement of the compensating winding and dial switch is shown in the diagrams attached.*



COMPENSATING LEVER

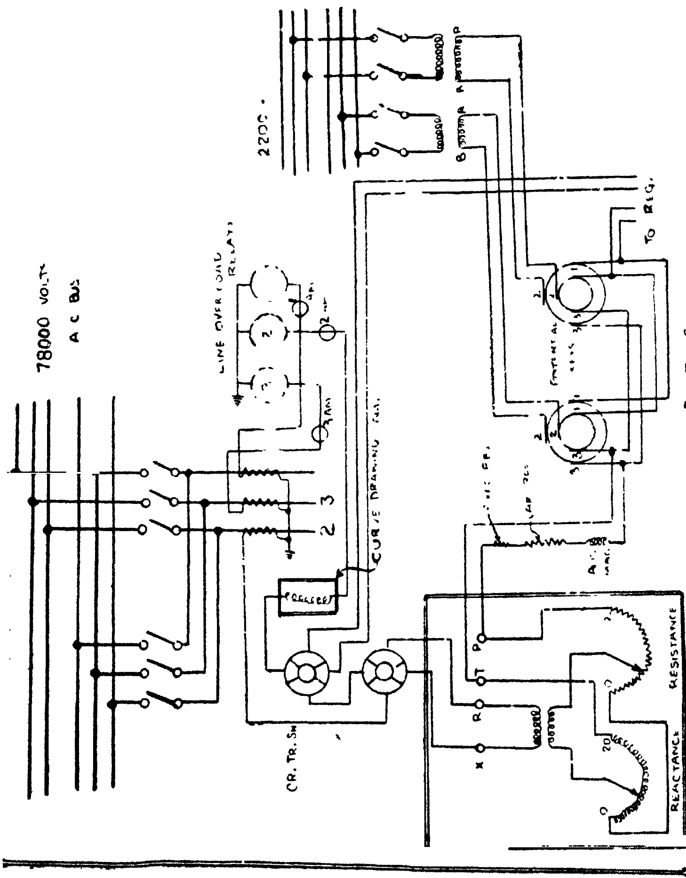
FOR VOLTAGE REGULATOR

Fig. 10·54

The compensating winding consists of three layers of wire, the two inner layers of which are connected as follows (Fig. 10·54):—The two terminals of the first winding are connected to buttons No. 1 and No. 2, while the other two terminals are connected to buttons Nos. 2 & 3. The second layer is divided into sections of five turns each, which have taps brought out to buttons 4 to 11 inclusively. Over these buttons, levers *A* and *B* are arranged to swing.

In order to increase the bus-bar voltage, the current in these windings should oppose the current in the potential winding. Therefore if with the load on the generators and the levers *A* and *B* swung to the right, the bus-bar voltage falls, it indicates that the current in the compensating winding is assisting the one in the potential winding, in which cases, leads 6 and 7 are reversed, with

regulator cut-out of service while making the reversal of connections. The opposing effect of the compensating winding is a variable factor depending upon the number of turns cut in by levers *A* and *B*, and also by the current flowing in the winding. Therefore, the amount of line-drop to be compensated is adjusted and found out



Line-drop Compensator Connections. Siva

Fig. 10'55

by trial tests, and levers *A* and *B* placed on buttons that will compensate for that line-drop to maintain the voltage constant at the centre of distribution from no-load to full-load.

The adjustment is best done by the following method. A portable voltmeter is obtained and with the dial switch on the regulator at the extreme left position, the regulator is carefully set to maintain 110 volts This setting is done under load condition, even with the dial switch levers in the position as indicated above. In making this adjustment, the test voltmeter is connected across the secondary terminals of the potential transformer connected to the regulator. This same voltmeter is carried to the point of the transmission line where it is desired to maintain the voltage constant; and connected to the secondary of a transformer (potential), giving 110 volts. This adjustment is made by an assistant at the power-station by adjusting the dial switch until the voltage at the end of the transmission line reads 110 volts. This adjustment is made under load condition, but not necessarily under full-load condition. If it were even made under half the load, the regulator will take care of a certain per cent. of a line-drop, and will maintain the voltage at this point at 110 volts under full-load or at any portion of the load

When once the two buttons, which correspond to the actual line-drop, are determined, no further adjustments of the levers are made and the voltage at the centre of distribution will always be correct for any load. The current transformer that is placed in the main lighting feeder, and compensates for the drop in that feeder, also varies the bus-bar voltage, which causes a corresponding rise in voltage in all the other feeders.

In all cases, the current transformers should be placed beyond the point, where any load, such as motor load, constant current transformers, etc., are taken of at the station, as the draught of current transformer, for such load would increase the bus-bar voltage as though the load were going out on the line which would be undesirable.

A current transformer that would give $3\frac{1}{2}$ amps. secondary will compensate for about 15% line-drop.

Occasionally, pressure wires are brought back from the centre of distribution and connected to the regulator to compensate for line-drop.

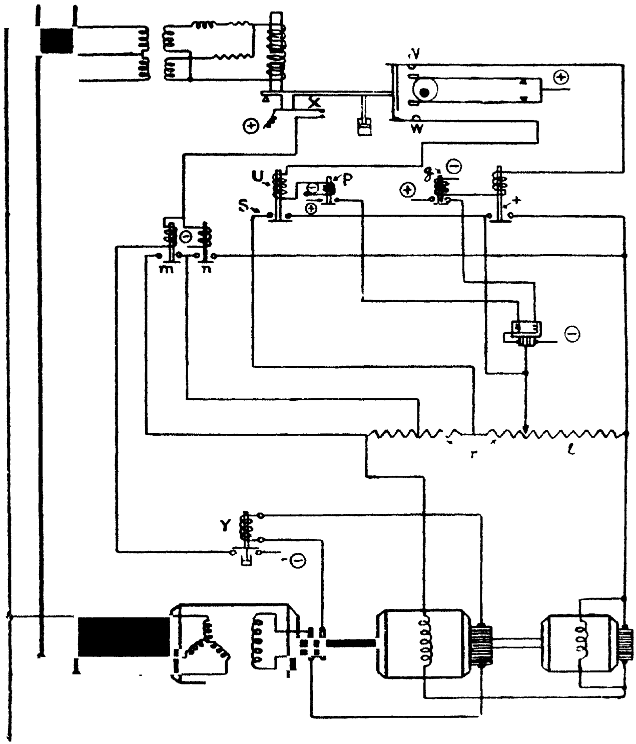
This arrangement will maintain constant voltage at the point where the pressure wires are tapped off the main line.

It has been found in bringing pressure wires back from the low tension network, that they are quite materially effected by varying the loads on the transmission lines and the error has been such that it was necessary to put in a transformer from raising the voltage from the low tension network, to 2,300 volts or more and then stepping down again to 110 volts for the regulator at the generating station.

This method of compensating for line drops *is not* considered as best in practice.

624. Field Forcing of Alternators as a Means of Increasing System Stability:--Difficulty is some times experienced in maintaining the stability of the system under fault conditions. This difficulty is aggravated by the phase angle between generating stations and the load centres, the displacement assuming increasing importance, the longer the transmission lines or the greater the impedance between stations. In fact, over extended territories the magnitude of the phase angle tends to determine the maximum K. V. A. that can be transmitted rather than the economic rating of the lines, for the reason that the smaller the angle under normal loading, the greater is the margin of stability under fault conditions.

A reduction, if it were possible, in the impedance between the feeding points would be of material assistance in improving the stability of a system. Also the installation of synchronous plant at strategic points would be of benefit. The extent of the latter amelioration is sometimes limited in practice, and on examination, the former shows that there is little scope for improvement in the characteristics of the transmission lines themselves, since the spacing of the conductors is the determining factor of their reactance beyond well defined limits.



Voltage Regulating and Field Forcing Equipment.

Fig. 10·56

There remain, therefore, the generating and the synchronous plant on which to concentrate efforts in the direction of securing a greater degree of stability.

Two directions, in which improvement is possible, are reduction of leakage reactance and an increase in the rate of exciter response to changes in machine voltage in order that the air gap flux may be better maintained under fault conditions.

The former is of importance, as the angle, subtended by the leakage reactance drops in synchronous plant, forms a considerable portion of the total power angle. As the magnitude of the power angle is a measure of stability between two points, any reduction in machine reactance effects an appreciable diminution in the total angle.

It is necessary to consider the behaviour of a machine with normal excitation control, on the occurrence of a sudden increase in load, in order to appreciate the need for means to build up quickly its excitation voltage.

The immediate effect of the increased load current is to cause a sudden drop in the terminal voltage due to reactive drop through the armature, and a strong demagnetising effect on the field. This de-magnetsing effect induces an abnormal field current which tends to maintain the flux at the original value, so that the machine flux diminishes relatively slowly. By the time the excess load is removed, the recovery voltage, dependent upon the remaining flux, may be insufficient to prevent the machine from falling out of step. Although the automatic regulator will have operated to increase the excitation, the response may be inadequate to check the flux from falling to a value at which the machine is unstable.

If therefore, the voltage across the D. C. field were increased at the incidence of the load change, the field current would be maintained and the de-magnetising effect would be counteracted with consequently little variation in the air-gap flux and generator voltage. As, at the initial stage of the load change, the induced current tends to sustain the machine flux, if it were possible to increase the exciting voltage to a value sufficient to

maintain the augmented current, the stability of the machine would be a maximum. At the earliest possible moment, therefore, the application of a high voltage to the field is essential.

If quick response excitation is to be effective, it is essential to provide means for automatically initiating the production of the ceiling voltage (is a term applied to the value of the exciter voltage obtained when all resistance in series with the field is short-circuited). This usually takes the form of an additional contact on the automatic voltage regulator which is only closed when voltage conditions outside the normal range of control occur. The need for the application of quick response excitation is indicated by a fall in voltage in the case of generators, synchronous condensers; and by lagging power-factor in the case of synchronous motors, the regulator usually being set to respond respectively to a reduction of 10 % in voltage or its equivalent in phase angle change. A single phase fault or heavy overload on a three-phase system may result in a reduction of two of the line voltages and an initial increase of the third. For this reason, the regulator must be capable of responding to a voltage drop across any phase. There are two ways of insuring this response, one being to use a three-phase winding on the regulator and the other to extract the positive phase sequence component of the voltage. The latter method has the advantage that the ordinary single phase control coil regulator can be used.

A provision of this nature is necessary, as otherwise faults on phases other than that to which the regulator is connected may cause an increase in the voltage on the regulator's control-coil and a consequent decrease in excitation at a time when an increase is most desired.

A simplified diagram of an alternator and its exciters arranged for field forcing together with a controlling regulator is shown in Fig. 10·56. An auxiliary exciter provides a source of constant voltage. The field of the main exciter is wound for about $\frac{1}{5}$th of the voltage and has, in series with it, a resistance.

Under normal conditions, regulation is effected on a small portion of the resistance in the exciter field circuit,

sufficient range being incorporated to cover all usual load requirements. To "force" the exciter field, the whole of resistance is short-circuited by closing of the contacts *m* and *n*, with small machines ; the full range of excitation is usually controlled by the regulator contacts, the limiting factor being the watts to be dealt with by the contacts, but for large machines, it is usually advisable to have seperate contactors to deal with the heavier currents for field forcing.

The automatic regulator shown diagramatically in the figure represents the most recent development. Instead of the usual method of voltage regulation by variation in the time ratio of 'in' and 'out' periods of a resistance in the exciter field circuit by continuously vibrating contacts, a motor operated rheostat is used which on this new form of regulator is controlled by 'high' and 'low' contacts. During the movement of the rheoshat, vibrating contacts are inserting or shunting a portion of the rheostat to maintain the desired voltage. Slow release relays *P* and *G*, energised by the vibrating contacts *W*, ensure continued movement of the rheostat to the portion corresponding to the correct voltage. An arm on the lever, controlled by the regulator solenoid, normally keeps the contacts *W* open. Any variation in voltage allows either the upper or lower contacts to close twice during each revolution of the cam which rotates four times per second. The time ratio of 'closed' to 'open' periods is governed by the degree of deflection of the regulator lever consequent upon the amount of departure from normal voltage.

This arrangement of variable rheostat and intermittent operation of vibrating contacts is a distinct advance on the older form using continuously vibrating contacts ; as it combines the advantage of the simple rheostat control with the quick action of the purely vibration-type.

Fault conditions on the system produce a tendency for the voltage to collapse, but when it is reduced to approximately 90 °/o of normal, the regulator contact *X*, or alternatively a separate low voltage relay closes to

energise contacts *m* and *n*. The contacts *m* and *n* pick up immediately to short-circuit the whole of the field resistance, forcing the exciter field current to rise to a high value, with greater rapidity. The application of the increased exciter voltage to the generator field prevents collapse of flux, thereby arresting the fall in the generator voltage.

The voltage applied to the field is in excess to that required to produce the current necessary to maintain the generator field flux at a pre-determined value; relay *Y* operates to interrupt the circuit of the contactor *m* which removes the shunt from a portion of the resistant *r* and reduces the exciter voltage to the appropriate value. By this means, the rate of increase of exciter voltage is 600 volts or more per second, for a 225-volt exciter, which would not be possible if the 'ceiling' voltage was only sufficient to produce the final value of the field current required.

LIGHTNING PROTECTION.

625. Lightning Phenomena :—The phenomena causing trouble in electric system may be divided into three general classes, as follows :—

1. High voltage
2. High frequency
3. High current

In any system of energy transmission, there are three types of phenomena causing strains; namely, steady stresses, impulses or blows, and vibrations.

In an electric system, high frequency and high voltage cause the same types of stresses, namely :—

(*a*) steady stress or gradual electric change, (*b*) impulse or travelling wave, (*c*) standing wave or oscillation and surge.

626. The Electric Charge :—The high potential difference between the ground and an electric circuit may gradually rise by the accumulation of an electric charge in the circuit, until the lightning arresters discharge or the insulation is punctured, depending upon

which is the point of least resistance. Some of the factors causing such a steady and gradual accumulation are :—

(*a*) The collection of static charge from rain, from snow drift, or from fog, carried by wind across the line.

The presence of accumulated static charge may be indicated by a series of periodic lightning arrester discharges.

(*b*) An accumulated static charge may follow the passing of charged clouds due to electro-static induction.

Assuming, for instance, a charged cloud passing over a transmission line, the ground below the line carries an electro-static charge of opposite polarity, corresponding to the charge of the cloud. The line shall also have a charge higher than that of the ground since projecting above it. If the line is insulated from the ground without the charge required for electro-static equilibrium, it appears at a potential against ground, that is, at cloud potential. With the approach of a charged cloud to the transmission line, the potential of the line against ground rises until a discharge takes place between the ground and line, charging the line to ground potential. Inversely, with the cloud receding from the line, the line charge is not bound by the charge of the cloud and therefore, discharges to ground.

(*c*) Potential differences between the line and ground due to differences of atmosphere potential in different regions traversed by the line, especially so, if the line passes through different altitude.

The danger of such accumulation of potential lies in the liability to damage the insulation of the system by the puncture or by their discharge, producing other or more serious disturbances.

627. Impulse or Travelling Wave :—An impulse or travelling wave is caused by sudden local electro-static charges on a transmission line, such as a lightning stroke, induced potential caused by the sudden discharge of a cloud, or any other sudden local change in conditions. This wave of potential and current travels along the line just as a water wave travels over the surface of the ocean.

The wave-front is very steep, *i. e.*, has high voltage at the point of impact, but gradually flattens out, and if the line is of unlimited length, ultimately disappears. If the line is of definite length, the wave is reflected and combines with the in-coming waves to form a system of nodes and maxima, called standing waves.

When an apparatus is connected to the line, the travelling wave divides ; part is transmitted, and part is reflected. The impulse is thus broken up into a number of secondary impulses, local standing waves, which may reach much higher voltages, than that of the travelling waves.

628. Impulse or Travelling Waves may be caused by :—

(*a*) Direct or Secondary lightning strokes, which generally do local damage, but do not travel far, as the disturbance is generally confined to a very few impulses of steep wave-front but of short extent.

(*b*) Electro-static induction from lightning discharges. While each of these impulses is rarely of sufficient power to do serious damage due to their frequency of recurrence, they may lead to the production of destructive internal surges. Impulses originating thus, are felt more generally through the system, but do not cause as much local damage as those originating from direct strokes.

(*c*) The discharge of slowly accumulated potential resulting in a series of successive impulses.

(*d*) Any spark discharge from line to line or from the line to ground.

(*e*) Arcing grounds.

(*f*) Sudden changes of load, switching, etc.

Impulses may be caused by external or internal disturbances; items (*a*) & (*b*) may be classed as external causes, (*c*) & (*d*) as both external and internal causes.

629. Standing Waves :—Standing waves are formed when a wave train is reflected, as the waves neutralise at some points forming a node, and add at other points forming a wave-crest, of greater or less amplitude than that of the original wave depending upon the phase relations of the original and reflected waves.

LIGHTNING ARRESTERS.

630. Lightning Strokes :—According to Sir Oliver Lodge, there are two different types of lightning strokes, A—direct stroke and B—induced stroke. The A-stroke is illustrated in Fig. 10'57. A charged cloud near the surface of the earth induces a charge of opposite type on all pointed standing objects such as church spires chimneys, etc. The electrostatic stress at the upper end of these objects is very great, and the air in the neighbourhood is rapidly ionised, streams of charged particles being repelled from all sharp corners and edges. Hence, the resistance of the discharge path between the cloud and the conductor is gradually lowered until a disruptive discharge occurs at the end which tends to equalise the potentials of the two bodies. This type of stroke takes longer time and is usually directed towards the highest and most sharply pointed object in the neighbourhood.

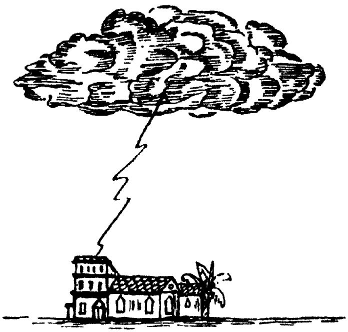


Fig. 10'57

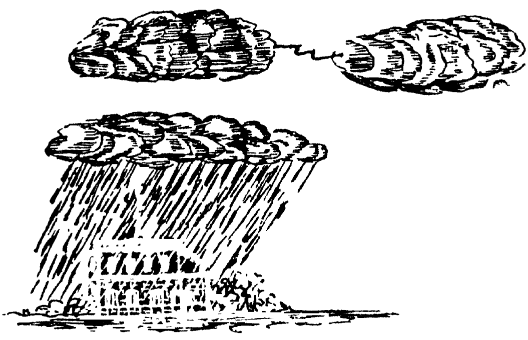


Fig. 10'58

The B-stroke is shown in Fig. 10·58. This is an impulsive rush of electricity occurring when the potential difference between the cloud and the earth is established almost simultaneously. It is generally induced due to a previous A-stroke. Thus, as shown in the figure, if an A-stroke occurs between the two charged clouds, the cloud below these may be left with a greater potential than the air can withstand and a B-stroke thus occurs to the earth. This type of stroke takes place with absolute suddenness and does not seem to obey any definite laws like that of the A-stroke. It may shatter a building, inspite of the presence of a neighbouring well-designed lightning conductor, or strike the ground even if there are tall objects such as trees or chimneys near by. Hence, B-stroke is far more dangerous than the A-stroke. Figs. 10·59 and 10·60 show other ways in which a B-stroke may occur.

Fig. 10·59

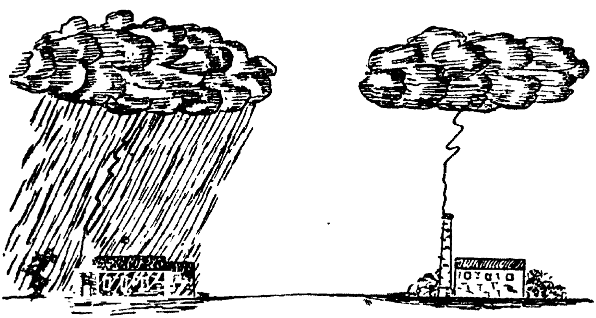


Fig. 10·60

Lightning stroke is one of the causes of rise of pressure. Methods of protection against this as well as other causes of rise of pressure are described in the following sections.

631. Lightning and Surge Protection :—Electro-static charge accumulates on the open conductors of a circuit at times when charged clouds are passing above the line, or by the gradual transfer from drops of rain, fog or snow as they touch the wires. The sudden release of a charge which accompanies a lightning stroke from cloud to cloud or to earth, liberates the induced charge on the line and causes an abrupt rise of potential which must find a way to earth. The effect of lightning discharge on electrical apparatus and lines can be direct and indirect. The effect of such discharge is due to (1) electro-static induction, (2) magnetic effect inducing an E. M. F. in the line (inductive surges may keep to the line and affect the apparatus in the power-station or may spark across the insulators and put the line to earth), (3) the lightning discharge actually striking the line on its passage to earth. A direct stroke will flash over the insulators and probably destroy the line at that point. There is a heavy rush of current and the resulting increasing pressure of the line may be high enough to pierce the insulation of any electrical apparatus or machinery connected therewith. The direct effect is the destruction of insulation. The indirect effect is the establishment of a low resistance circuit which may be maintained by the normal voltage of resistance circuit which may be maintained by the normal voltage of the system.

Cables laid underground cannot be directly affected by lightning but the insulation of the cable may be punctured, if it is connected to an exposed overhead line. If underground cables are used to carry ærial lines across a street, the overhead earth wire should be brought down also and wound on to the cable sheathing, and earth plates should be provided at each side of the crossing. The ground connections must be carefully made and must be ample, the artificial grounds with iron pipes are much increased in effectiveness if these are wetted with salt water occasionally.

SPARK ARRESTERS are installed at the ends of high tension underground system, to prevent high voltages which might injure the insulation in case of sudden changes in load, grounds and short-circuits. Overhead lines, specially when they run at greatly varying levels, are very liable to be affected by lightning and atmospheric discharges.

632. Principle of Lightning Arresters :—Lightning arresters divert or dissipate the energy of the discharge and promptly interrupt any low resistance circuit that may be established for the purpose of diverting or dissipating the energy. Hence, suitable lightning arresters must be used for protecting the supply lines or any support or guard wire or bearer wire of an electric supply line.

The voltage being inconceivably high and the discharge being of a variable, high frequency, oscillating character, the discharge takes the least inductive but not necessarily the best conducting path to earth.

The choking coils C_1, and C_2, placed between the connection to arrester and the station apparatus, are used to impede the violent surging of current, at enormous potential, and the flow of current to the bus-bars is impeded by offering a much higher resistance than the earth connections to the gaps G_1 and G_2. Therefore the discharge

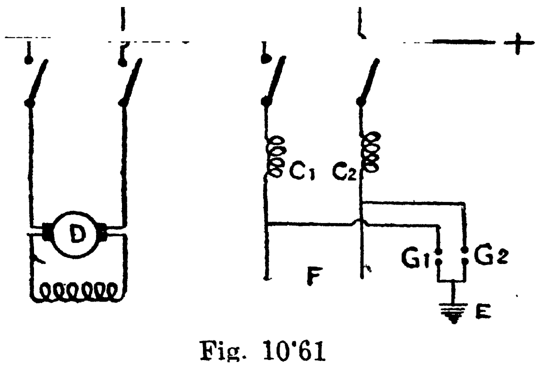
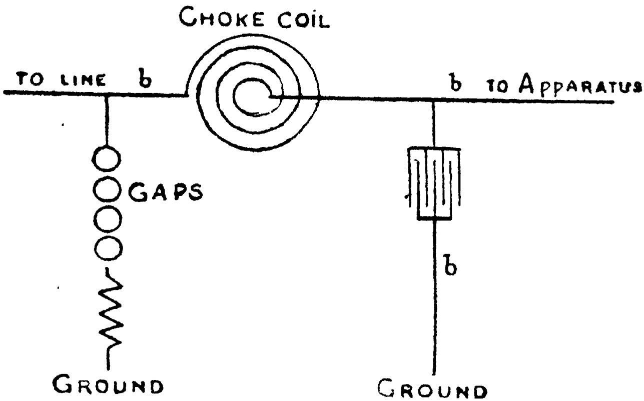


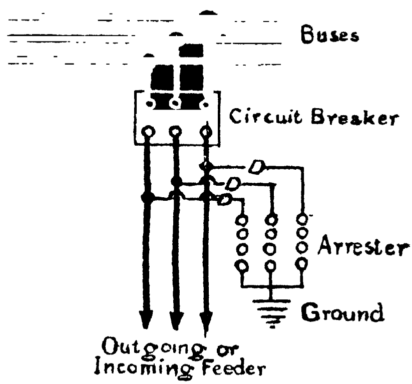
Fig. 10'61

current passes to earth through G_1 and G_2 instead of



Relative Positions of the Component Parts of a Lightning Arrester.
Figs 10·62

puncturing the insulation of the machinery and controlling apparatus connected to the system. An arc is set up which bridges the gap and now the generator pressure, though not of sufficient magnitude to start the arc, may be high enough to maintain the arc; if allowed to continue, it would destroy the arrester and may permit in some cases an excess flow of current as to overload the generators or other apparatus connected to the line. Hence, such an arc, consequent at discharge, must be extinguished by some



An Installation of Feeder Lightning Arrester.
Fig. 10·63

method. To avoid the gradual building up of statical potential to an unsafe value, which cannot be prevented by the choke coil, the spark gap resistance is made considerably less than the insulation resistance of the machinery and apparatus protected, and it must be adjusted to such a length that the normal pressure of the generators is insufficient to bridge it.

Note.—The ground connections should be inspected and adjusted frequently and a sufficient number to be provided to give a combined resistance as low as two or three ohms.

633 The Requisites of a Lightning Arrester are as follows:—

1. The value of abnormal voltage at which discharge will begin. An arrester must be capable of being adjusted to begin to discharge at a value of voltage reasonably between the normal rated line voltage and the test value of safe dielectric strength of the apparatus insulation. The sensitivity to be desired depends upon the inherent sealing or arc rupturing characteristics of the arrester and the voltage regulation or fluctuations of the system voltage.

2. The discharge rate of the arrester or impedance of the arrester under discharge must be commensurate with the service conditions likely to be imposed. The discharge rate is recognised as one of the most vital factors in satisfactory arrester performance. When a severe lightning disturbance is induced on an electric system, it may involve an enormous quantity of electric energy. The arrester must have sufficiently low internal impedance to instantly discharge all of the over-voltage energy to earth.

3. The arrester should discharge over-voltages without permitting flow of generator or line current for more than two or three half waves of the generator voltage.

This factor is very important in the interest of smooth operation and the absence of sudden short-circuit currents through the arrester which, when finally interrupted cause a sudden re-adjustment of electro-static and electro-magnetic energies which may build up serious surges or localised oscillations. An arrester should

preferably possess perfect valve characteristics which would permit the over-voltage to be discharged to earth but prevent any flow of current to earth when the voltage has been reduced to normal.

4. The arrester including any series gap, which may be used, should possess negligible dielectric spark lag. This requisite is of great importance, since the majority of over-voltages to be discharged from electric circuits are of the nature of impulses or travelling waves with abrupt or steep fronts.

5. The arrester should always be ready for successive multitudinous discharges. The majority of lightning flashes are multitudinous ; that is, the flash may be composed of several individual flashes following each other in rapid succession. Each one of these distant flashes produces *over voltage transients* on electric systems. This characteristic of lightning, together with the recurring discharges possible from switching, arcing grounds, and the other abnormal conditions in the electric circuit producing over voltages, make it important that the arrester is always ready for successive discharges

It must be remembered that a lightning arrester is an over voltage device, and the *selection of the arresters* must, therefore, always be based on the normal line or generator voltage of the circuit. Arresters are generally rated with minimum and maximum voltage values. It is not generally safe to apply an arrester to a circuit where the maximum dynamic voltage will exceed, even for a very short period, the maximum voltage rating of the arrester. Arrester ratings refer to R. M. S. or effective value of sine wave.

634. Types of Lightning Arrester :—There are various types of lightning arresters of which the following are worth mentioning :—

(1) Horn-gap arresters. (Burke type etc.)
(2) Multi-gap arresters.
(3) Electrolytic arresters—Aluminium arresters.
(4) Oxide film arresters.
(5) Autovalve arresters.
(6) Crystal valve arresters.

(7) Thyrite arresters.

(8) Surge absorption arresters.

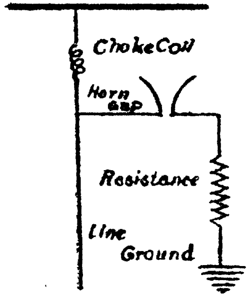
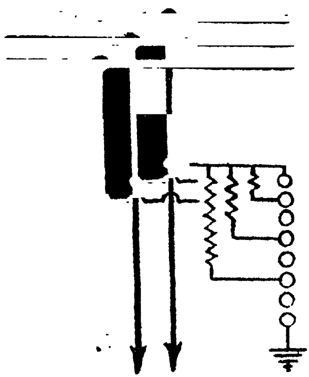


Fig. 10'64

Fig. 10'64 is a simple horn-gap arrester together with a resistance. Fig 10'67 gives the horn-gap arrester in conjunction with the aluminium type lightning arrester.

Fig. 10'65 shows the multi-gap arrester with resistance elements in parallel, only connection to one phase has been shown. This requires frequent removal of dust by blowing with compressed air.



Multigap Arrester with Resistance Element in Parallel.

Fig. 10'65

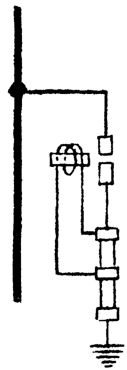
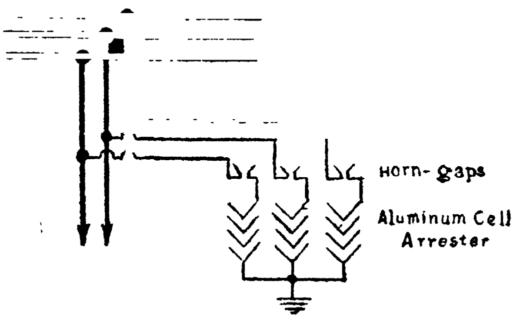


Fig. 10'66

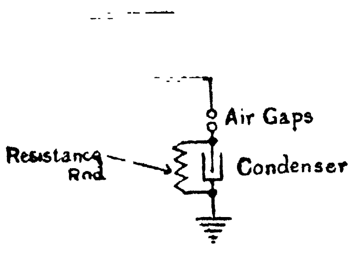
Fig. 10·66 shows arrangements for magnetic blow-out of the arc produced in the spark gap lightning arrester.



Aluminium Cell Lightning Arrester.

Fig. 10·67

Fig. 10·68 shows spark gap lightning arrester in conjunction with a resistance and condenser connected in parallel, as something additional is needed to limit the flow of dynamic current after relieving the excess potential. The most common use is to protect transformer secondaries, a single gap per bank of transformers being used.

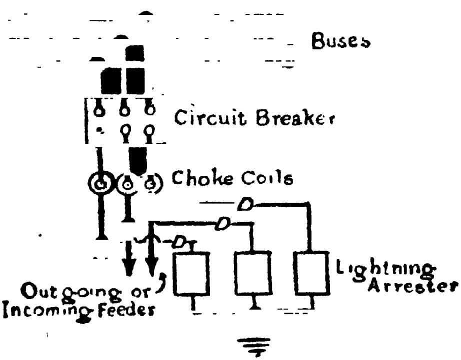


Condenser lightning arrester

Fig. 10·68

635. Aluminium Lightning Arrester :—Arresters of this class are also called, *Electrolytic Arresters*, and depend for their action on the phenomenon that a conducting

film is formed on the surface of aluminium immersed in certain electrolytes. If the film is, however, exposed to a higher pressure, a pressure more than 350 volts per cell, it may be punctured by many minute holes, thus so reducing its resistance that a large current may pass. When the pressure is again reduced, the holes become resealed and the film again becomes effective. It is used in conjunction with a horn gap which has the effect of insulating the arrester from the line excepting during the lightning discharge. It is the best of all arresters at high transmission voltages. Its disadvantage is that it is more costly than air-gap arrester and requires a little attention. It should be charged everyday, that is connected across the line without an air-gap in series to keep the insulating film in good condition. The horn-gap arrester itself is capable of dealing with heavy surges but it can only operate on an over-voltage and is useless on a low voltage, high frequency surge. A useful setting is to be 1 mm. per 1,200 volts plus 1 mm. to prevent constant discharge. Fig. 10 67 shows the arrester with the horn-gaps in series. It is therefore, necessary to charge the cells from time to time, and thus prevent the dissolution and consequent rush of current which would otherwise occur when the arrester discharges.



Relative Positions of the Component Parts of the Aluminium Lightning Arrester.

Fig. 10'69

It is not suited for out door distribution work, since it requires daily charging and supervision and cannot be left continuously in circuit.

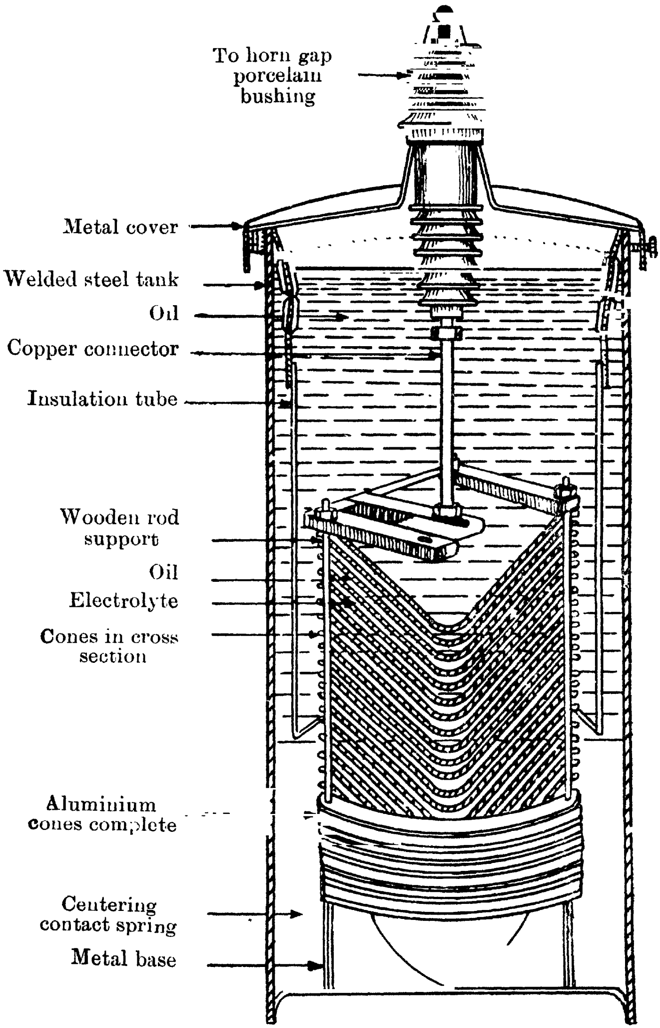

To horn gap porcelain bushing
Metal cover
Welded steel tank
Oil
Copper connector
Insulation tube
Wooden rod support
Oil
Electrolyte
Cones in cross section
Aluminium cones complete
Centering contact spring
Metal base

Fig. 10·69 (*a*)

The protective quality of the arrester depends on the valve action of the aluminium cell opposing the flow of current at normal voltages and allowing a free flow at abnormal voltages, due to lightning or such other disturbances. The condenser action of the stack of aluminium cells also contributes to the protective value as it is effective in the discharge of high frequency currents. Fig. 10·69 shows the relative connections of lightning arrester choke-coils and circuit-breaker.

ERECTION AND CHARGING.

636. Filling of the Cones with the Electrolyte :—The cones are not filled till every other thing is ready to put the arrester into service on the line. The cones are thoroughly cleaned with petrol and fitted well. They should be kept clean and protected from any dust or dirt. A clean glass, leather-ware vessel is used in handling the electrolyte. The cones are protected from any moisture gathering in, and the cones are filled with the required amount of electrolyte.

To facilitate the filling of the cones, a filter is sent along with each arrester purchased. The electrolyte container is raised about 2 feet higher than the cone stack to be filled. The cone filter is fastened to a rigid vertical upright stick. The cone filter tube is filled with electrolyte. Hold rubber tubing which fastens to a pinch cock until the rubber tube is full of electrolyte. Close the pinch cock and stick the free end of the rubber tube with a piece of glass piece in it to prevent the tube from floating on the surface of the electrolyte in the electrolyte container. Open the pinch cock and see if the siphon works and the electrolyte flows freely into the cone-filter tube. The pinch cocks are located as near the filter tube as possible, otherwise, the amount of electrolyte measured will not be correct.

A systematic method is adopted for checking such as marking the edge of the cone with a pencil or using a little wedge of wood to make sure that each cone has been filled and no cone has been over filled. The electrical test, being made after filling, will show any empty or any

over-filled cell. If a cell was to be found over-filled, the excess electrolyte is carefully siphoned out.

637. Preliminary Testing of Cells :—As soon as each stack of cones is filled with electrolyte, each cell in the stack is tested to see that the films are properly formed and the cells are properly filled with electrolyte.

Starting with the bottom cell of the stack, the hand-made test plug is inserted between the two cones of the cell. Note if there is any spark at the time of inserting the plug. If there is no spark, it means an empty cell. This will also show upon the ammeter. If the cell is alright, read the voltage and current, and they are watched whether the current decreases and the voltage increases. As for a good cell the voltage should increase until there is practically full circuit voltage across the cell, and the current should decrease to 0·2 to 0·4 of an ampere, depending upon the frequency of the test circuit. This testing and charging takes about 10 seconds per cell. A comparison of the voltage across each cell with the applied voltage will indicate the condition of the film. The current will give an indication of both the film condition and plate area, all the other conditions being the same. A double filled cell will take approximately twice as much current as a properly filled cell. A line is marked with chalk on each cone as it is being filled and after being tested complete. As a check on the testing, when each cone stack is tested, one lead of the test circuit is connected to the cone base and then with the other lead a make-and-break contact is made on the top cone. If there is no spark, it indicates the presence of an empty cell.

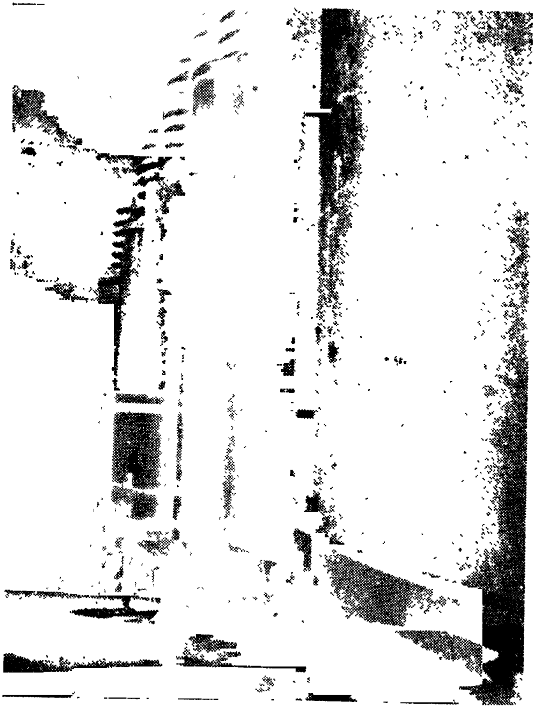
638. Daily Charging of Cells :—In order to keep the cone film in perfect condition, it is necessary to connect the arrester stack to the line one or more times each day. This daily charging or film forming operation is done at a time of the day when the line voltage is at a maximum. To operate the charging mechanism, quickly and securely, short-circuit the upper horn-gaps for at least five seconds. Then operate the charging mechanism until the gaps are in the disconnected position. The

transfer device is reversed which interchanges the connections to the ground stack of cones and are of the live stacks. This operation of charging and re-disconnection is repeated a second time. The gaps are tested whether any of them is left short-circuited, for if the arrester gaps are left short-circuited accidentally, the oil and the electrolyte will overheat resulting in serious damage. Besides checking the gaps, the spark developed at the time of making and breaking the contact is observed, (size and colour) which shows the conditions of the cells.

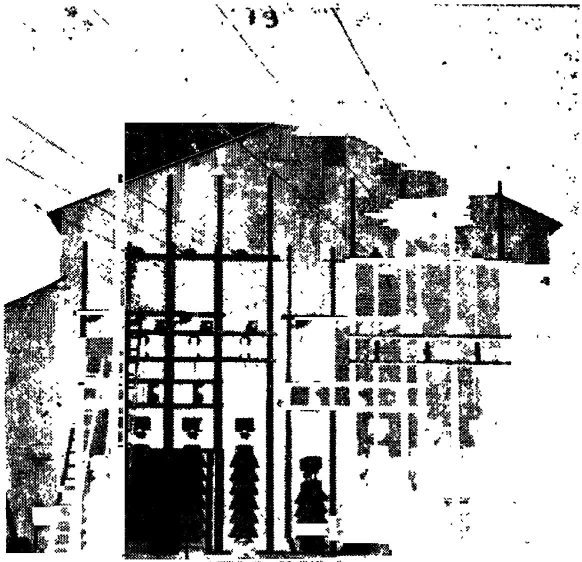
639. Charging Current Indicator :—The charging current indicator is a device for indicating the condition of the arrester cell. It is designed for all voltages and consists essentially of an ammeter of low inductance mounted on a specially constructed switch stick, and a set of jacks. The jacks are very easily attached to any aluminium arrester and are so connected in the arrester circuit that, when the switch stick is inserted in them, arrester gaps are short-circuited and all arcings in the arrester circuit are eliminated, and the charging current flows through the ammeter. An arrester in good condition has a charging current of approximately 0 2 amp. at 25 cycles and 0·3 amp. at 40 cycles. To measure the charging current of an arrester, first close the gaps until the flexible contacts make a perfect contact and all arcings are eliminated. This is very important as the smallest possible arcing makes the reading unreliable. The gaps are held in this position when the ammeter stick is inserted into each jack and the current read. The gaps are then opened to disconnecting position until the transfer device has been changed and the method of reading repeated for the four stacks. The ammeter tanks or insulating rack should not be touched when charging current indicator is inserted, as, they are at high voltage of the system and are therefore dangerous.

640. The Oxide Film Arrester is another form of "valve" arrester adaptable to all voltages, A.C. and D.C. and is offered by one manufacturer in preferenee to the aluminium arrester. It consists essentially of a stack of cells in series with a gap. Each cell consists of two

brass discs separated by an annular ring of porcelain, the interior space being compactly filled with lead peroxide powder which has a low resistance. A film of varnish on the side of each brass disc in contact with the lead peroxide provides sufficient insulation to prevent appreciable current flow at rated voltage, which is about 300 volts per cell. A series gap is used to prevent the very slight leakage current that would otherwise flow at rated voltage. At abnormal voltage, the gap is broken down and the varnish films are punctured. The current flow is proportional to the excess voltage. The action of the current on the lead peroxide is to form red lead and litharge, which immediately seals up the punctures, restoring the insulating value of the original varnish film, and the arrester is again ready for duty.



Oxide Film Lightning Arrester.
Fig. 10'70

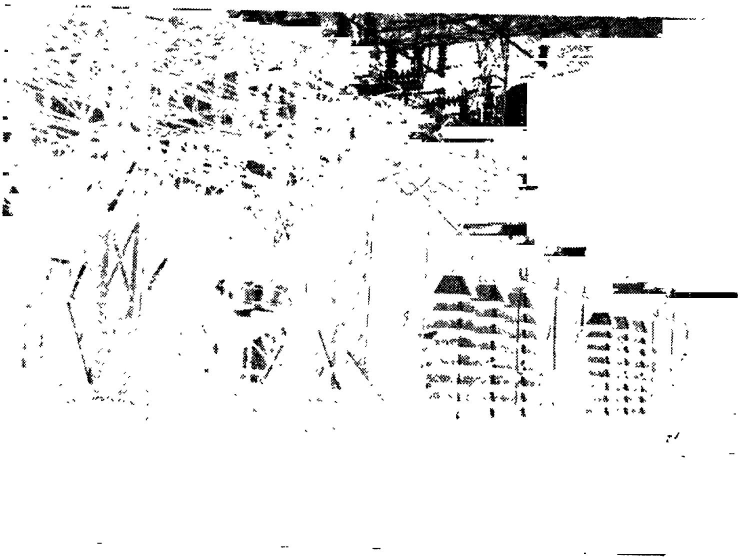


Oxide Film Arresters Equipment for H. T. 35,000-volt, Double Circuit Lines.

Fig. 10'71

641. The Pellet-type Arrester is a modification of the oxide film type and is particularly adaptable to distribution circuits. The lead peroxide is formed into small pellets about the size of ordinary pills, which are coated with an insulating powder, and placed in a porcelain chamber between two electrodes. In this way, each pellet, with its insulating powder covering, constitutes a miniature cell corresponding to the larger and

less numerous cells of the oxide film arrester. A gap is used in series.



Oxide film Arrester at Sub-station, Pykara.

Fig. 10·72

These cells are hermetically sealed by the metal of the electrodes being spun over the procelain separating ring. The cells can be installed both outdoor as well as indoor, requiring, in outdoor installations, merely some protection by petticoats, to keep the rain from short-circuiting the cells. These are protected with sphere-gaps, to give instantaneous discharge, with a horn attachment to allow the arc flare up and thereby help in its extinction. The plain horn-gap has the disadvantage of requiring an appreciable—though a very short (micro-seconds time lag for discharge) and an extremely sudden high voltage, as a very steep wave front may pass over the horn-gap and face elsewhere. Therefore, in modern lightning arresters for high voltages, the horn-gap is shunted by a properly

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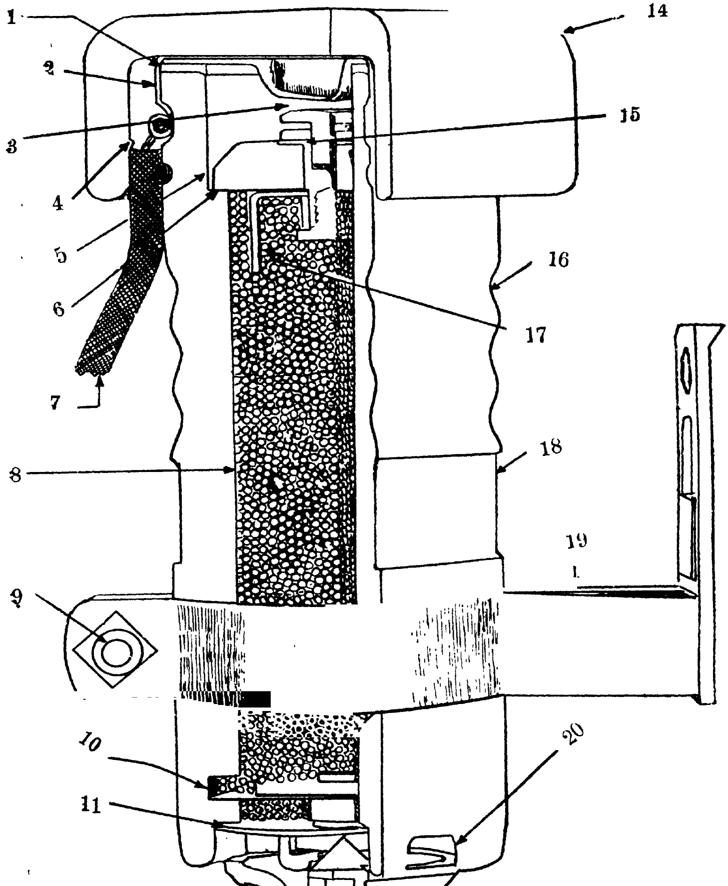


Pellet Lightning Arrester.

Fig. 10·73(a)

(1) Sealing gasket.

(2) Metal cover bottle-cap-crimped over porcelain.

(3) Single series gap in sealed chamber.

(4) Compound secures porcelain cap.

(5) Glazed seal between porcelain insert and container-tube.

(6) Wet-process-porcelain insert isolates sealed gap chamber from pellet valve-column.

(7) No. 6 B and S flexible rubber-covered weather proof line lead 18-in. long.

(8) Pellet valve-column.

(9) Bolt soldered to prevent turning in hanger when nut is tightened.

(10) Recess inside of container-tube provides rigid non-twist lock of terminal stud assembly to container-tube.

(11) Bottom-plate with name plate data on lower surface.

(12) Stop-ring on stud prevents complete removal of nut, lockwasher, and clamp.

(13) Removable molded cover.

(14) Wet-process porcelain cap.

(15) Sealing gasket.

(16) Wet-process porcelain container-tube with corrugated surface.

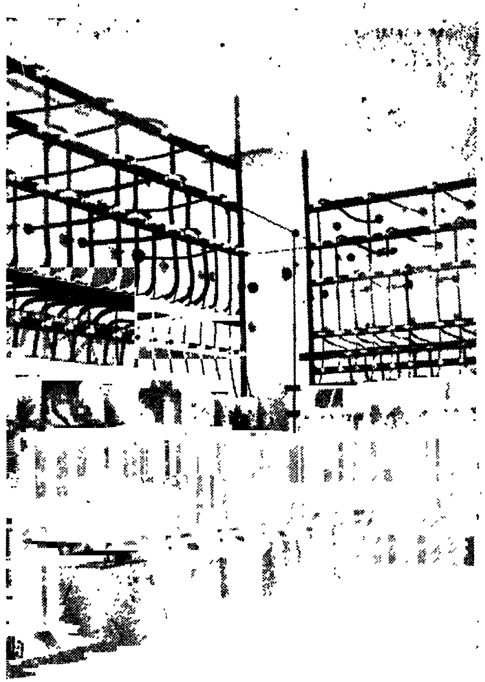
(17) Contact sleeve.

(18) Extra groove for alternate position of hanger.

(19) Double-galvanized steel hanger.

(20) Openings for ground leads are on opposite sides container-tube.

proportioned sphere-gap, the latter being instantaneous in action. Whenever these are installed in outdoors, rain lowers the discharge voltage of the sphere-gap, and thus requires a setting which gives a higher discharge voltage in dry weather than necessary. So a protective sphere-gap is used to overcome this disadvantage in the open sphere-gap. Thus the arrester does not discharge voltages lower than the discharge voltage of its spark-gap, even if these lower voltages may cause some danger to the system by their high frequency. Such low voltages, while they cannot endanger the main insulation between circuit and ground, may, if of sufficiently high frequency, lead to local accumulation of voltage across the inductive parts of circuit as regulators, current transformers, end turns and coils of generators and transformers and there cause damage by puncturing insulation between turns and causing internal short-circuit.



A Pellet Lightning Arrester Installation.
Fig. 10·73

When a lightning voltage sparks over the gaps, it is impressed on the cells and breaks down the insulating

coating on the metal plates; the break-down occurs in the form of a small puncture of the film coating, but the metal plates are not punctured. As soon as the film gives way, a discharge current flows through the cells to ground, thus relieving the lightning pressure. The flow of current through the cells immediately causes a chemical change, by heat, in the lead peroxide at the point of puncture. The lead peroxide is changed to red lead and litharge, which have a very high resistance. Thus, following the lightning discharge, a very high resistance, amounting practically to insulation, is automatically cut into the discharge path. This cuts off the flow of generator current that would otherwise follow the lightning discharge, and the arcs in the gaps die out. If the potential should still, or again, be sufficiently high to break down the gaps, the operation is repeated at some other point on the surface of the varnished plates.

The arrester requires no more than the usual inspection and attention given to other kinds of electrical apparatus, except that *an inspection should always be made at the beginning and end of each lightning season.*

A means is provided for occasionally testing the cells of arresters for voltages above 7,500, to determine whether any have been deteriorated to such an extent as to be useless. This device consists of a calibrated gap in a glass vacuum bulb mounted on a testing stick, with contacts which can be placed against the metal plates of the cell. The arrester is short-circuited on the line, and this causes a drop across the cells in proportion to their resistance. A cell of high resistance will have a large drop and will cause the bulb to glow. The cell can then be easily removed and a new one inserted. It is recommended that the arrester be tested only at the beginning and end of each lightning season.

The cells are connected in the familiar multiple arrangement, which gives, for three-phase arresters, two sections of cells between any pair of lines and two sections between any line and ground. The arrester, therefore, consists of four legs arranged in four stacks for voltages up to 73,000; while for higher voltages each leg is arranged for two stacks to secure the desired mechanical stability.

The stacks are mounted on insulating racks, and arresters for outdoor service have galvanised sheet-iron louvres attached to the wooden supports, to give protection against the weather, as shown in the illustrations. These louvres can readily be removed for inspection or repairs.

All oxide film arresters for voltages above 7,500 are connected to the line through spark-gaps of a hemisphere type. The small leakage current with this type of arrester makes it unnecessary to use horn-gaps to aid in breaking the arc, and it is further more possible to cover the gap. This is of the utmost importance for outdoor arresters, as rain greatly lowers the 60-cycle spark-over voltage of all uncovered gaps, and thus imposes an increased setting and consequently decreased protective value of the arrester, since the high-frequency lightning spark-over voltage is not changed by rain. The covered sphere-gap, therefore, gives the maximum protection, since it can be set for a minimum voltage value with dry weather, and the protective value will be constant under all conditions.

This is used on voltages from 1,000 to 220,000 for both indoor and outdoor service. The station type is made up with both open and enclosed gaps. This last being the later development

Oxide film arresters do not require charging like the aluminium-cell arrester, and the absence of oil reduces the fire hazard.

Note :—An arrester should not be applied to a circuit outside of the range of voltage indicated by the manufacturer. If it is used on a lower voltage, the protection will not be so good as could be obtained ; while, if used on a higher voltage, the arrester will be too sensitive and will probably be damaged.

642. Auto-valve Arrester :—This is one of the most modern developments for the protection of transmission lines from the effects of abnormal pressure rises. It was originated by Slepian and is essentially a multiple spark-gap type of arrester, but makes use of a glow-discharge instead of an arc-discharge. A structure composed of a column of flat electrodes, separated by

insulating spacers of the thickness to give gap lengths of 3 to 5 mils, will operate as a valve, the critical glow-discharge voltage being approximately 350 volts per gap over a wide range of current values.

In the commercial form, the arrester is made up of a series of disc electrodes of a material having suitable resistivity, each pair of discs being separated by mica spacers. Each column of gaps is connected between line and earth through a series-gap. The number of gaps is chosen so as to give one gap for each 200 volts (R. M. S.) between line and earth, thus providing a voltage margin of approximately 25 % before break-down occurs. The disc area is selected to give a resistance rather lower than the electrodes.

This type of arrester has the advantage over the electrolytic type in that the initial cost and maintenance charges are lower, and it does not require daily attendance. Hence, it has a wider field of application.

Sphere gaps give the highest obtainable speed (or minimum time-lag) of discharge from the most dangerous kind of lightning disturbances, *i. e.*, impulses of steep wave front. When a 60-cycle voltage is slowly applied to a gap and gradually increased, spark-over will occur at some definite voltage. This is the minimum voltage that will cause sufficient ionization for the gap to discharge, and it requires a relatively long time.

643. Crystal Valve Arrester—Construction and Operation :—A lightning arrester is essentially an electrical safety valve, and its operation may be quite correctly compared with that of an ordinary steam safety valve. Such a safety valve remains closed until the pressure rises to a 'certain critical pressure,' when it opens and relieves the steam line of 'excess or dangerous pressure,' closing when the pressure falls to normal.

A valve-type arrester such as the 'crystal valve' has a certain 'critical voltage' and when it arcs over due to huge surge voltage, permits surge currents to flow, thus relieving the electrical circuit of 'excess or dangerous voltage' ; when the surge voltage falls to the 'critical voltage', the arrester 'closes' up and of course stops the

flow to ground. A lightning arrester has one chief function—that of protecting electrical equipment from lightning or other high voltages; being connected directly to a power circuit, it must also possess a secondary function—that of preventing or suppressing the flow of system or power current that may follow the lightning discharge to ground.

To function as an electrical safety valve, to efficiently protect electrical equipment from lightning and to suppress any flow of power current that may follow the lightning discharge to ground, the C. V. A. is constructed essentially of one or more spark gaps in series with what is known as a 'characteristic' element. The function of the spark gap is to keep the circuit through the arrester open under normal conditions and to spark over and close the circuit through the arrester when the surge voltage has reached a pre-determined value depending on the setting of the gaps. The function of the characteristic element in conjunction with the gaps is to impart valve characteristic, as to the arrester.

644. General Constructions:—The mechanical assembly of the crystal valve arrester is quite simple and is shown in the accompanying illustration Fig. 10·74*a*; it consists of an art process porcelain body '*A*' with art process porcelain cover '*B*'; this body encloses a certain number of spark gaps '*C*' and the characterstic element '*D*' which is a tightly packed mass of highly refractory crystals to which the name "Crystallite" has been given. The general features of mechanical assembly are quite clearly shown and will not be further commented on. Line and ground leads are provided as shown and the arrester is mounted to the cross arm or other suitable support by means of mounting bracket '*E*.'

645. Operation:—The fundamental features, underlying the operation of the C.V.A. are quite simple, are readily understood and will be explained in the following paragraphs. Suppose, first of all that we connect a test circuit such as shown in Fig. 10·74; here we take a porcelain tube '*T*', pack it tightly with a mass of "crystalline" crystals '*C*' and provide metal end plates

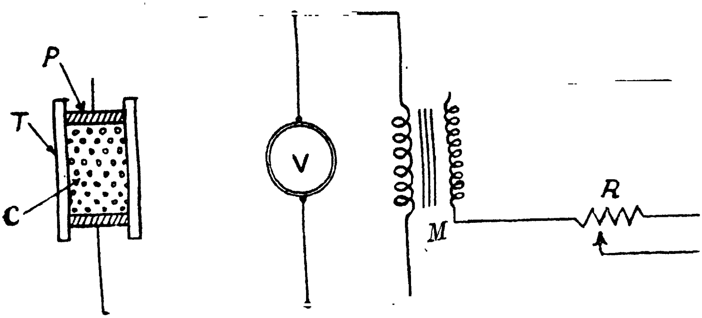


Fig. 10·74

'*P P*' to make electrical contact with the ends of the crystal mass; a voltmeter '*V*' is connected across the crystals as shown, an ammeter '*A*' is connected in series with them and arrangements provided to impress voltage across the circuit, as for example, by variable voltage transformer '*M*'; '*R*' shows a resistance in the primary circuit of the transformer which may be used to vary the secondary voltage. We can now apply a number of different voltages across the crystallite, reading this voltage by means of the voltmeter '*V*' and at the same time reading the current through the crystallite by means of the ammeter '*A*.' By obtaining the proper and corresponding values of peak voltage and current, we can readily calculate the resistance of the crystallite for any given value of applied voltage. Let us run this particular series of tests with applied voltages upto, say, 5,000 volts. Plotting these values in the form of a curve, as shown in Fig. 10·75, *we see that as the voltage across the crystallite increases, its resistance decreases.*

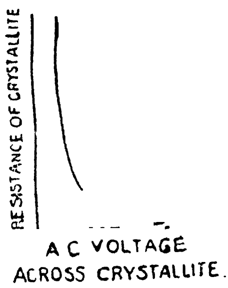


Fig. 10·75

Suppose now that we continue these voltage current measurements at voltages above 5,000, using for this purpose the lightning generator connected in accordance with Fig. 10·76 in which "*y—y—y—y*" show the condensers of the lightning generator, '*M*' the main voltage control

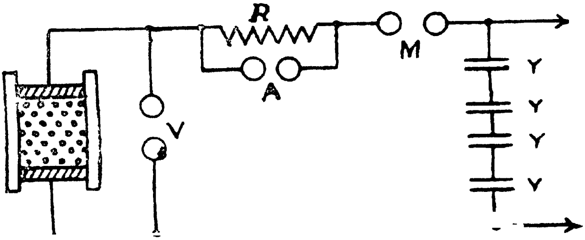


Fig. 10·76

gap, '*R—A*' a resistance spark gap combination for measuring the impulse or surge current flowing through the circuit and '*V*' a spark gap for measuring the impulse or surge voltage applied across the crystallite. We can now do the same as before, apply a series of different surge voltages across the crystallite, measuring their values by means of gap '*V*' and the corresponding values of surge currents by means of gap '*A*' and resistance '*R*'. Having thus found a number of corresponding values of volt and current, we can readily calculate the *resistance* of the crystallite for any given value of applied voltage. Plotting these latter values in the form of a curve as shown in Fig. 10·77, we again see that as the voltage across the crystallite increases, its resistance decreases, and by comparing this figure with Fig. 10·76 that this decrease in resistance with increase in voltage follows identically the same law whether the voltage is high or low or whether it is direct current, A.C. or

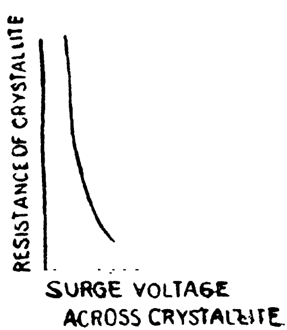


Fig. 10·77

impulse current from lightning generator. If the voltage resistance characteristics of crystallite be drawn on logarithmic cross section paper as shown in Fig. 10·78 proof will be obtained, since this curve is a perfectly straight line that the same identical law is followed for all values of applied voltage. This curve shows a change in resistance from 10 miliohms to ·1 ohm for a corresponding change in applied voltage from 100 to 100,000 volts; crystallite—characteristic element of the C.V.A.—therefore has the remarkable property of being practically an insulator at low values of applied voltage and of being a very good conductor at higher values of applied voltage.

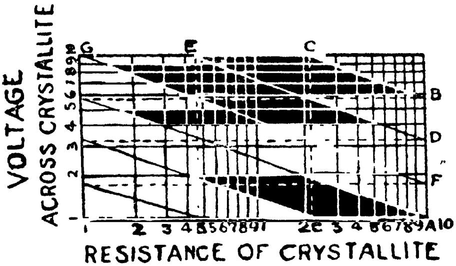


Fig. 10·78

This is one of the most important characteristics of crystallite, ideally adapting it to lightning arrester service, and was first described in connection with C.V.A. as early as 1926.

These voltage/Resistance phenomena, it will readily be seen, is the basis for what we can properly call an electrical safety valve which is operated or actuated solely by the magnitude of applied voltage. If the voltage is below certain values, the valve remains "closed." That is, its resistance is so high that practically no current flows through it; as the voltage rises, the valve "opens", resistance dropping to very low values, which permits heavy current to flow through it, and when the voltage drops again, the resistance immediately increases to its initial high value, so causing the valve to "close" and permitting practically no current to flow through it.

In the actual C.V.A., a spark gap or gaps are placed in series with the crystallite, the addition of this gap isolates the crystallite from the circuit to which the arrester is connected and imparts to the arrester certain definite

values of volt at which it begins and ceases operation. With this in mind, we can now go to the actual operation of a C.V.A., and see how it functions under normal service conditions.

Let us assume that the arrester is for 3,000-volt. distribution service and that the spark gap is set to arc over at 6,500-volts. Let us assume that a lightning surge is set free on the circuit, this surge having a voltage high enough to force a current flow of 1,000 amps. through the arrester. This surge voltage reaches the point on the line at which the arrester is connected and in an infinitely small time interval, builds up to the voltage required to arc over the gap; since the gap construction of the C.V.A. is such as to practically eliminate time lag, the arrester begins to discharge when the surge voltage reaches a value of 6,500. At this instant, the crystallite has a certain definite conductivity and surge current immediately starts to flow to ground. The surge voltage applied to the terminal of the arrester continues to increase as the peak of the surge approaches the point of the line to which the arrester is connected and since *crystallite itself has no time lag*, just as quickly as the surge voltage increases, the resistance of the crystallite decreases and permits more and more of the surge energy to flow to ground, until when the maximum current of 1,000 amps. is flowing through the arrester, its resistance has decreased to the low value of about 15 ohms – a resistance so low that the lightning surge is literally 'dumped' to the ground; all of this, as later shown by typical cathode ray oscillograms, have occurred in a few millionths of a second due to the extreme speed of the C.V.A.

As the surge energy flows to the ground through the arrester, its voltage decreases and consequently the voltage across the arrester decreases, the resistance of the arrester then automatically increases and in a few micro-seconds has reached such a high value that in conjunction with the action of the gap the arrester "seals up" and all current flow therethrough ceases. This sealing up does not occur until the voltage of the surge remaining on the line has been reduced to a value which is entirely harmless to insulation of the transformer or other

electrical equipment which the arrester is protecting. In order to secure the highest degree of protection to electrical equipment, it is necessary to limit the surge volt applied to it to as low a value as possible and for the shortest possible time; since a lightning arrester is connected in shunt to the apparatus which it is protecting, the measure of protection afforded by the arrester will depend on how low it can hold the surge voltage and on how quickly it can dump the surge energy to the ground. Both of these factors depend largely on the resistance of the arrester during operation and the lower this is, the quicker will the lightning surge be carried to ground and the smaller will be the voltage built up across it due to the flow of surge current through it.

The C.V.A. as has been shown, controls both these factors in a most beautiful manner, for the resistance of the crystallite automatically changes depending on the voltage applied to the arrester and the surge current flowing through it; for any given surge voltage and current, the resistance of the crystals will have a given value; as the surge voltage and current increases, the resistance of the crystals decreases and so automatically adjusts itself to the severity of the lightning discharge.

If, for example, the lightning surge has voltage sufficient to cause a surge current flow of 250 amps. through a 3,000-volt distribution type C.V.A., its internal resistance will be approximately 41 ohms. If the surge current-flow is 1,000 amps, the internal resistance-drop will be 15 ohms approximately, at 2,000 amps. to approximately 9 ohms and so on. This condition is shown graphically in Fig. 10'79 and shows precisely why C.V.A. can successfully handle surge currents of extremely large magnitude and afford efficient protection to electrical equipment under the most severe lightning conditions.

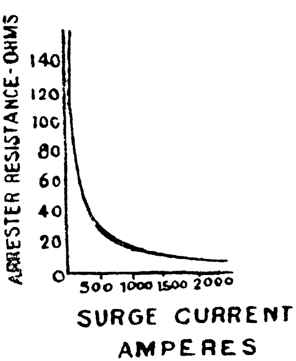


Fig. 10'79

With these facts relative to the value and impedance characteristics of the arrester clearly in mind, it will now be possible to quickly follow through a typical arrester operating cycle by means of cathode-ray oscillograms. Fig. 10'80 shows graphically a test voltage surge which is

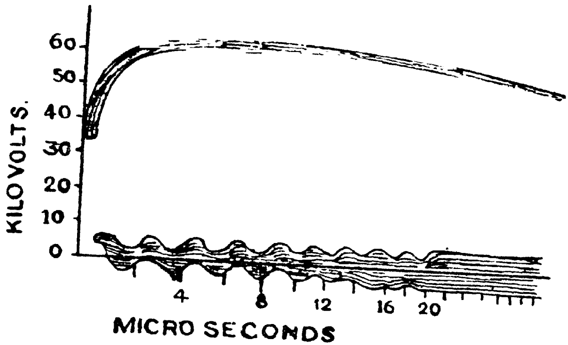


Fig. 10'80

impressed across a 3,000-volt distribution type arrester. This surge, initially at the rate of 50,000 volts per micro-second, reaches a value of 55,000 volts and is maintained as shown in illustration.

Such a surge voltage strikes the arrester and in a

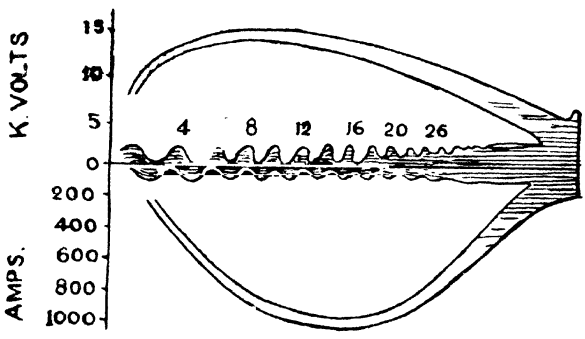


Fig. 10'81

fraction of a micro-second has risen to the arc-over voltage

of the arrester which then spills over and begins to discharge; surge current then starts to flow through the arrester and in about 13 micro-seconds has reached a value of 1,000 amps., see Fig. 10'81. During these 13 micro-seconds, the arrester resistance or impedance has decreased from an infinitely high resistance to the low value of approximately 15 ohms, see Fig. 10'81 and 10'82. Current then starts to decrease and at the end of 45 micro-seconds, the valve actions of the arrester close it up and the operating cycle has been completed. From the 13th to 45th micro-second note that the arrester resistance or impedance has increased from approximately 15 ohms to an infinite value represented by the arrester in its closed valve condition. Fig. 10'83 shows graphically the volt-time characteristics of the initial surge voltage wave, the reduction in this by the arrester and the time required for the complete cycle of operation.

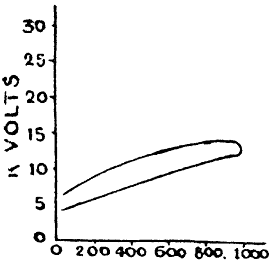


Fig. 10'82

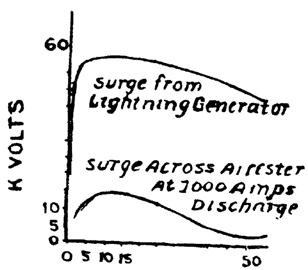


Fig. 10'83

The operation of the arrester has involved the two fundamental characteristics, *i.e.*, the valve characteristic and impedance characteristics, both actions are entirely, according to unchangeable physical laws, initiated, actuated and controlled by the characteristic of the lightning voltage impressed across the arrester; there are no chemical and physical changes occurring within the arrester; there is nothing within the arrester requiring exact structural arrangement of parts for its proper operation; its operation boils down to the analogy of a plain, simple safety valve which opens up at a certain pre-determined voltage and where discharge capacity varies according to the magnitude of the surge volts

and currents which the arrester must carry to ground ; the discharge capacity becoming greater as the severity of the surge becomes greater ; and being based on these unchangeable physical laws, the C.V.A. will operate thousands or tens of thousands of times with no measurable deterioration giving the user, the utmost obtainable in the way of efficient, absolutely reliable and lasting lightning protection.

The most convincing proof of all of the foregoing lies in the highly successful performance of the hundreds of thousands of C.V.A. which are in service in all parts of the world and in every conceivable condition of operation.

646. Thyrite Lightning Arrester :—

This is the latest type of arresters produced by the General Electric Company and has the requisite characteristics of an arrester for maximum response to that duty and affords an excellent protective device and has unique features.

(*i*) This arrester permits of the accurate pre-determination of performance, allowing positive co-ordination of arrester voltage to station apparatus insulation.

(*ii*) The valve element—Thyrite—has the characteristics common to both lightning and system voltages and has no time lag.

(*iii*) The interchangeability of the arrester units from one voltage rating to another provides unusual flexibility in the arrester application.

(*iv*) The physical arrangement requires no maintenance costs.

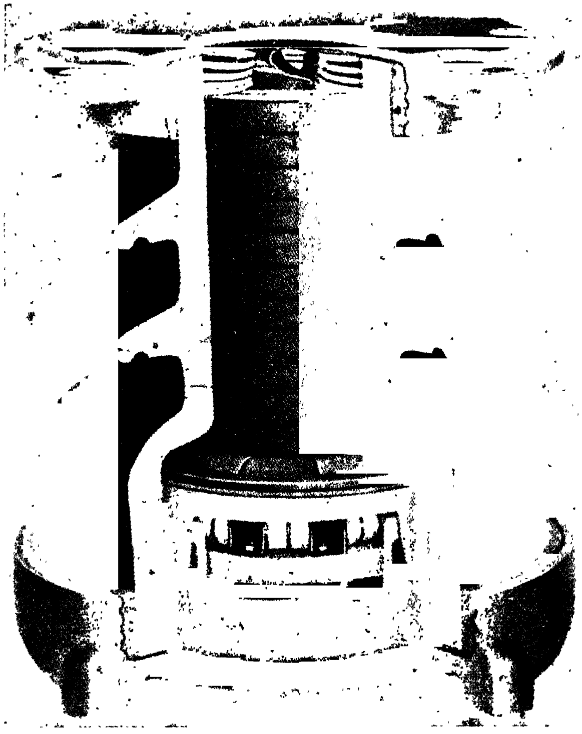
(*v*) The arrester may be applied either indoor or outdoor for the protection of large or small generating or sub-station equipments on either grounded or ungrounded systems over a very wide range of voltage.

Thyrite Lightning Arresters.

Fig. 10 84

647. Thyrite :—A dense, homogeneous, inorganic compound of cormic nature, perfectly stable and mechanically strong. The remarkable material has the unique characteristic of being substantially an insulator at one voltage and becoming an excellent conductor at a higher voltage. The electrical resistance of thyrite is a function of voltage only, the resistance decreasing and the current increasing 12·6 times, each time the voltage is doubled. Thyrite adheres to this characteristic law indefinitely without change regardless of the rate of voltage application

for either continuous or alternating potential. Thyrite can be produced in any shape that can be successfully moulded. For arresters, thyrite is made in discs sprayed with metal on both sides to provide contact surface. Each disc is 6″ diameter and $\frac{3}{4}''$ thick and has an active area of 28 sq. in. and a volume of 21 cu. in. Each is rated approximately 1 K.V. (R.M.S.) at system frequency; and the flash-over distance of $\frac{3}{4}''$ per K.V. rating is sufficiently liberal to permit thyrite to discharge several



11·5-K.V. Thyrite Arrester Unit with Section cut away to show Interior.

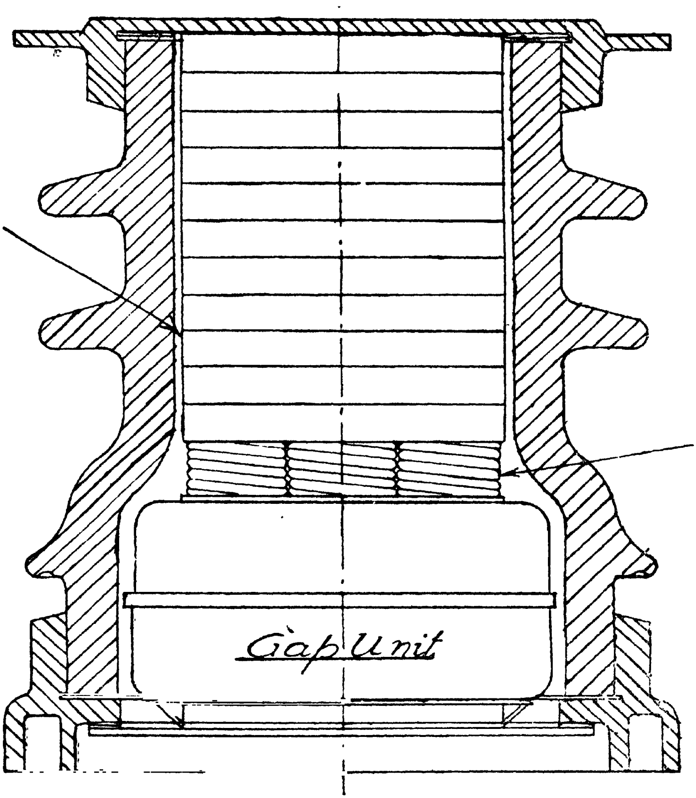
Fig. 10·85

thousand amperes without the slightest tendency to flash over the outside edges. Thyrite will not puncture or shatter when subjected to most severe discharges.

648. Thyrite Arrester Units :—Various number of thyrite arrester units are stacked in series to constitute the arresters of different voltage ratings. The arrester as a whole does not have a gap (series gap), each arrester unit being complete within itself and containing its own gap structure. The standard unit is rated at 11·5 K.V. (R.M.S), so that multiples will confirm to N.E.L.A. ratings. The unit consists of 11 discs in series with a gap assembly, all housed in a glazed porcelain container. The unit is fitted up with top and bottom castings of heat treated aluminium comparable with malleable iron in strength, but lighter in weight and requiring no painting or weather resisting treatment. The castings are secured to the porcelain housing by steam cured cement.

The gap assembly is placed at the bottom of the arrester with cushion contacts at top and bottom providing pressure connection. The standard arrester unit is 13″ diameter and 15″ high and weighs 1,000 lbs. net.

649. Arrester Assembly :—The thyrite arrester units are assembled together by bolts inserted in the holes in the top castings and threaded into the bottom castings of the adjacent unit. The complete assembly includes a base casting of malleable iron with hot dip galvanised finish and with provision for attaching the foundation bolts The lightning arrester, like strings of insulators, requires provision such as the graduing ring for improving the voltage distribution when more than a certain number of units are connected in series. The lower the normal applied voltage per unit, the greater the number of arrester units that can be connected in series before the graduing ring must be used. This ring is made of hot dip galvanised pipe. It is attached to the top arrester unit and extends down concentrically around a few arrester units.

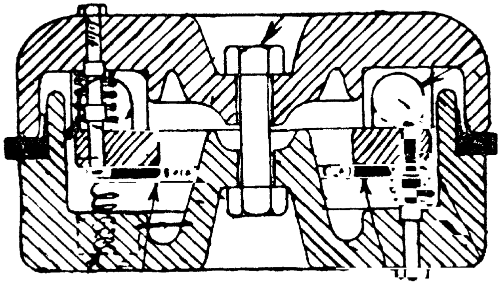


A Cross Section of the Thyrite Arrester.

Fig. 10'86

650. Thyrite Arrester Ratings :—These arresters are rated in terms of line-to-line system voltage (R. M. S. value). From 1 to 9 K. V., the arresters are given a maximum and minimum voltage ratings. In this range, the same arrester is used either to grounded or

ungrounded neutral circuit. Above 9 K. V., they have

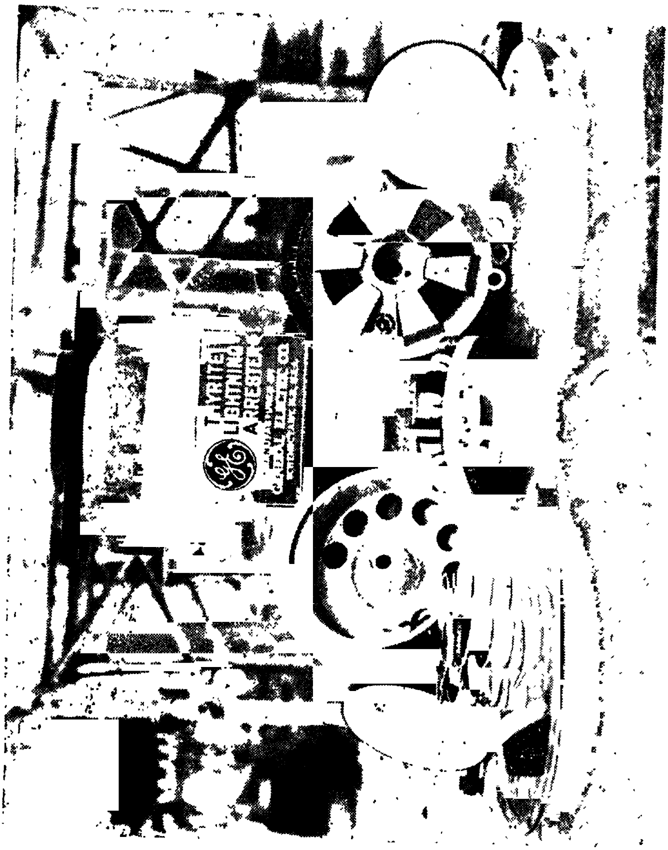


Gap Unit of the Thyrite Lightning Arrester.

Fig. 10·87

a normal voltage rating corresponding to standard N. E. L. A. system of rating ; and a maximum voltage rating representing the maximum sustained R. M. S. operating voltage of the circuit for which the arrester is suitable. They also have a maximum permissible line to ground voltage rating which is the maximum R. M. S. line to ground voltage which the arrester will withstand, and which should, therefore, never be exceeded.

651. Thyrite Arresters for Grounded Neutral Circuits :—The solidly grounded neutral system permits the application of a reduced arrester units, giving better protection at lower cost. Arresters for solidly grounded neutral system have approximately 50 p.c. of the number of arrester units in the design for ungrounded neutral circuits, providing a margin of approximately 38 p.c. in the arrester ratings for rises above the normal system line voltage to ground. The interpretation of "solidly grounded" in this connection is that the neutrals of all generating or other sources of power fed to the circuits shall be permanently connected and directly as well, to



Dismantled Parts of the Thyrite Arrester.
Fig. 10·88

low resistance ground with no intervening reactors, resistances, fuses or switches. The location and reliability of neutral grounds must be such that with any system of switch operation, the arrester can never be energised by an ungrounded neutral source and the system neutral will be definitely fixed at earth potential.

652. Protective Performance of Thyrite Arresters:—Accurate prediction can be made of the protective performance of any thyrite arrester for any assumed conditions of installation; first, because the break-down voltage to start discharge is independent of wave fronts; second, because the volt-amp. curve has no loops, insuring a definite voltage for each value of current regardless of duration of current flow. This makes possible a definite co-ordination of voltage allowed by arrester with the lightning strength of the station or apparatus insulation. The voltage required to start discharge is independent of rate of change or magnitude of the applied voltage wave and is directly proportional to the number of arrester units between line and ground. The impedance voltage depends upon the value of discharge.

653. Inspection and Care:—Before inspecting, disconnect the arrester from the line, and as a safety precaution, ground the line end.

The thyrite arrester requires no special care; however, porcelain parts should be kept clean and connections tight. Remove undergrowth or other obstructions.

To place the arrester again in service, remove the temporary ground from line end and close the disconnecting device.

654. Instructions for Assembling Thyrite Units:—

1. The units should be stored and assembled in a dry place.

2. Remove circular plate from bottom casting of porcelain housing.

3. Place triple spring into housing. Put thyrite discs into housing.

4. Remove the large composition nut in the centre of the gap unit, and remove the porcelain gap cover. In order to do this, it will not be necessary to disconnect the flexible strap connection between the cover and the gap ring.

5. Examine the gap unit to ascertain that each pair of gaps is properly located between the spring contact clips.

6. Examine the small resistance rods on the bottom side of the gap ring. Should any rods be broken, a replacing gap unit should be ordered from the factory.

7. If all parts are in good condition, replace the gap container, being particularly careful that each contact spring enters its respective cup. Replace the gap cover on the gap container and tighten the centre nut just sufficiently to engage the cover and cork ring.

8. Place the gap unit in the housing with the cover side adjacent to the thyrite disc.

9. Replace circular plate and tighten.

10. **Caution :**—If the units after assembly are stored out of doors, care should be exercised to see that they are stored with the bottom casting down to prevent the accumulation of moisture.

655. Surge Absorption Arresters :—These protect apparatus on one side from any surge coming from the other side. They consist of either helically wound coils, with the energy dissipator in the form of a cylinder surrounding the coil, or spirally wound sections in disc shape between two flat sheets of metal which form the energy dissipator. The cylinder or the sheet of metal forming the absorber is earthed. The voltage drop and watt loss at 50 cycles are negligible.

Principle :—The inductance coil of the absorber acts as the primary winding of a transformer, the energy dissipator forming a secondary winding of one short-circuited turn. The losses due to the secondary current induced in the dissipator and the high eddy current losses at surge frequencies (20,000 cycles and upwards) are responsible to a large extent for the effectiveness of the absorber. The absorption co-efficient of the arrester has been found to be 85 per cent. These are connected in series with the transmission line.

656. Compression Chamber Arrester :—The essential element of the compression chamber arrester is a small air-gap between two electrodes of non-arcing metal (zinc alloy) separated by a porcelain spacer. During discharge the gases, held in the small chamber formed by the electrodes and spacer, become somewhat compressed and assist in extinguishing the arc. This feature gives

the arrester its name. This type of arrester is designed for protection of secondary lighting and power circuits.

657. Voltage Rating of Arresters :—

		Feet clearance.	
		Min.	Min.
Min.	Max.	Indoor.	Outdoor.
1,000	15,000	3′	5′
15,000	37,000	4′	6′
37,000	73,000	6′	8′
73,000	161,700	10′	10′

658. Operating Stand :—The operating stand, by which gaps are operated for daily charging, is located in such a position that the operator can clearly see the gaps and the spark that takes place.

659. Instruction for Installing Lightning Arresters :—

Location :—The location of lightning arresters necessitates electric plants to be divided broadly into two groups :—

(1) Plants in which there are numerous and widely distinct pieces of apparatus, in respect of the location of lightning arresters, of each individual type, such as, transformers, motors, arc lights, etc. In such cases, lightning arresters should be located to protect the whole line. The location should be at a number of points, such that the parts of the line particularly exposed may have more points than those that are naturally protected, *e.g.*, by tall buildings or numerous trees. It is impossible to make any definite statement of the number of arresters needed per mile, as the requirements vary widely in different cases. Under average conditions, no point of the circuits should be more than 1,000 feet from an arrester. For circuits of over 2,500 volts with distributed apparatus, though this is of rare occurrence, special protection should be made by placing a lightning arrester as near as possible to each piece of apparatus.

(2) In plants in which there are pieces of apparatus at a few definite points in the system, as for example, in a high voltage transmission line, the arresters should be located for the purpose of protecting those points

where apparatus is situated. In other words, the location should be such as to protect the apparatus rather than the line as a whole.

Connection :—Connections for lightning arresters should always be made in such a way that in passing from the line to the apparatus, the arrester is reached first, the choke-coil second, and the condenser, if there is any, third.

Insulation :—A lightning arrester is naturally exposed to severe voltage strains. As such, all its active parts must be well insulated ; proper insulation is easily secured on arresters of low voltages, as the construction of the arresters itself affords protections. In the case of high voltage arresters, however, proper insulation is a difficult matter. As a general rule, all arresters are marble or porcelain mounted, the marble or porcelain serving as an insulating support for the arrester. For circuits exceeding 6,000 volts, further insulation is necessary. This is secured by mounting the marble or porcelain bases on wooden supports, well dried and shellaced. For 12,000 volts and above, the bases or panels are provided with an additional insulation in the form of porcelain or glass insulators used as supports.

Two high-voltage arresters connected to different line wires should never be placed side by side without either a barrier or a considerable space between them.

In selecting the **location for an arrester,** the following points are carefully considered :—

(1) **Safety first** :—Arresters should be guarded by a guard rail or screen to prevent accidental contact of operator with any live parts.

(2) **Indoor Arresters** :—Indoor arresters should be installed in fire-proof compartments separated from other apparatus.

(3) Increased insulation is required above 400 ft. elevation, or where insulators and tank bushings are subjected to deposit of cement dust, smoke, etc.

(4) Special painting should be given to exposed metal parts subjected to acid or alkali fumes.

(5) For maximum protection, the arresters should be installed where the arrester cone stacks will not be exposed to excessive heat or cold.

(6) Series gaps are located either indoor or outdoor to obtain sufficient clearance over the top of the horns for the arc to raise under abnormal conditions.

(7) **Ground** :—Much importance is laid on the making of good ground connections which should be as short and straight as possible. With a poor ground connection, all efforts made with choke-coils and lightning arresters to divert static electricity into earth are rendered ineffective. So, for efficient result, it is not sufficient to make a good ground connection only, but to maintain it so.

Satisfactory grounds can be made by driving one inch iron pipes to the permanent moisture level, and then salting the ground around the pipes to a depth of several feet. The ground should be kept thoroughly moistened. Two or more such ground pipes, spaced at least six feet apart to get the maximum benefit of each and bussed together by means of heavy copper wire, or preferably flat copper strip, make an excellent arrangement for station ground. The number of arrester grounds depends on the character of soil and the size of the arrester installation. For the average power or lighting station, the installation of four such ground pipe arrangements will suffice. These should be located near each outside wall of the station and bussed together solidly. One of the groups should be installed at a point nearest the arrester or a fifth one put in at such a point. It is advisable to put these earth pipes connected to the iron frame-work of the station and also to any water mains etc. as may be available. In no case should there be less than 2 pipe grounds installed, and where accurate records are to be kept of ground resistance, at least three such pipe grounds should be made with the individual pipes 6 ft. or more apart.

Dependance should not be placed on a long ground lead for a lightning arrester ground connection. The high frequency impedance of a long ground lead is a much more vital factor in the problem than extreme low

resistance of the ground connection itself. A pipe ground should be made directly at the arrester installation, connecting this ground to the other station grounding system.

The actual electrical efficiency of the ground connection can only be determined by a measurement of its resistance. The resistance of a single pipe ground, properly installed and maintained, has an average value of about 15 ohms. Where there are at least 3 ground pipes not less than 6 ft. apart, the actual resistance of each ground can be determined readily and accurately. With these grounds identified as *A*, *B* and *C*, the series resistance of *A* plus *B*, *B* plus *C*, and *C* plus *A*, can be obtained by the "fall of potential method." The solution of the three equations gives the resistance of individual grounds. Connect a 100-volt or 220-volt A.C. or D.C. supply through a regulating rheostat and an ammeter across two of the pipes. The function of the rheostat is to regulate the current to a safe value 5 or 10 amperes, if the ground is of low resistance. The drop across the two grounds should be measured by a suitable voltmeter, allowing a few minutes after closing the circuit for constant conditions to be reached. The voltage drop, divided by the current gives the amount of the two resistances in series.

The arrester is considered alive at all times unless disconnected from the line by opening the disconnecting switches.

A good ground connection for a bank of station arresters may be made as recommended by the Westinghouse Company in the following manner. First, dig a hole four feet square as near the arrester as possible, until permanently damp earth has been reached ; second, cover the bottom of this hole with crushed char-coal (about pea size) ; third, over this lay 10 square feet of tinned copper plate ; fourth, solder the ground wire, preferably No. O copper, securely across the entire surface of the ground plate ; fifth, cover the ground plate with crushed char-coal ; and sixth, fill the hole with earth, using running water to settle.

The method of making a ground connection, described above is simple, and gives very satisfactory results

But, still, if not made in proper soil it will prove of little value; if the location is made near a mountain stream, the ground plate is sometimes conveniently thrown into its bed. The ground contact in such cases, however, is not satisfactory owing to the high resistance of the pure water and the rocky bottom of the stream. Materials such as clay, even when wet, rock, sand, gravel, dry earth and pure water are not at all suitable for burying the ground plate of a bank of lightning arresters. Rich soil is considered to be the best for the purpose. Hence, the selection of the best possible site for the lightning arrester installation, with reference to a good ground connection, is necessary before installing a bank of choke-coils, and lightning arresters. Such selection may, as a matter of course, be often at a little distance from the station when the construction of a lightning-arrester house becomes a necessity. Where permanent dampness cannot be reached, some arrangement for supplying water to the ground through a pipe from some convenient source must be made. An excellent ground is obtained by a direct connection to an underground pipe system, specially of town or city water main. For, this provides the great surface of contact of the pipes with the earth and numerous alternative paths for the discharge. In water-power plant the grounding should always be made to the pipe-line or penstock, and to the case or frame of the apparatus to be protected.

An effective and simple grounding may be made by using a large, old iron casting such as an old car wheel with a riveted copper strap and buried in damp soil. For maintaining dampness, a quantity of common salt may be thrown around any ground terminal before covering.

In addition to equipment referred to, it is usual to connect the earthing leads to the power-station circulating water-pipes. The form most favoured is the cylindrical earth-pipe, as it is possible to get the same amount of earth contact surface into a much smaller space. For instance, a plate 6 ft. wide could be replaced with equal efficiency by a pipe 2 ft. in diameter and the saving in excavation would be considerable. Such pipes in their simplest form should be closed at the lower end and the

end as well as the body of the pipe should be perforated. The inside of the pipes should be packed with fine coke and the pipe buried in the bed of coke. Recently, another form of earth plate has been proposed consisting of a hollow conical shaped apparatus which is filled with coke and stones, and the one advantage of this appears to be that a better contact may be maintained with general mass of earth.

Inspection and Maintenance :—In any earthing installation, it is necessary that every special attention be paid to the question of maintenance, particularly as regards the conductivity. Moisture naturally tends to drain away from the plates or pipes and, therefore, provision must be made for periodically and regularly watering the ground, while the conductivity is further increased by applying salt on top. The passage of current through the installation further dries out the surrounding coke and earth, and this should not be lost sight of.

660. Choke-Coils :—The choke-coils should be located between the arresters and the apparatus to be protected, so that an in-coming surge will meet first the arrester and then the choke-coils. The functions of the choke-coil are to hold back the lightning disturbance from the generator or transformer until the arrester has time to discharge to earth, and to lower the frequency of whatever part of the disturbance passes through the coil, so that the wave front is not so steep as to cause a serious rise in potential across the end coils of the transformers or generators.

Choke-coils for high voltage work are of two general designs, the stationary-type and the suspension-type. The stationary choke-coil is formed of bare copper wire, supported on insulators which are mounted on steel bases. The indoor coils have post insulators ; the outdoor coils, petti-coat insulators. The advantage of this type of choke-coil is that the turns are air insulated from each other. Should there be arcing between turns in the case of extremely heavy disturbances, the turns will immediately re-insulate themselves.

The suspension choke-coil consists of a strain insulator having a bare copper coil wound concentric with its axis.

The coil is held securely at each end and is kept from sagging in the centre by one or more brackets.

661. Arcing Ground Suppressor:—The arcing ground suppressor is used with non-grounded system. Its use is also limited to steel tower lines, as on a wood-pole line the resistance of the pole is liable to prevent sufficient current flowing to ground to reduce the potential sufficiently to operate the relay.

The arcing ground suppressor, as generally built, consists of three single-pole, independent, motor-operated oil switches, electrically and mechanically interlocked, to prevent more than one operating at the same time. Each switch is connected to ground on one side and to the line on the other. The suppressor is controlled by a phase selecting relay, which remains inactive while the system is balanced, but when it becomes unbalanced, because of a ground on one phase, it operates the corresponding phase of the suppressor, which, in turn, grounds the same phase of the line, thus shunting the current and extinguishing the arc. The switch is then automatically opened and will remain so, provided that the ground was only temporary, such as an insulator spilling over. If the ground is of a permanent nature, as when caused by the puncture of an insulator, the switch will immediately close a second time and be locked in the closed position until opened by hand after the ground has been removed. Should the switch stay open for a fraction of a second after the first stroke, however, the second stroke device would become inoperative, as it only comes into action when the switch starts to close the second time immediately after the first time. To prevent the possible operation of the suppressor in cases of short-circuits, an overload relay, which opens the control circuit of the suppressor may be provided.

662. Short-circuit Suppressor:—This device operates on the same principle as the arcing ground suppressor, but it is intended on grounded systems where any arc to ground would form a short-circuit. The suppressor is connected between each line wire and ground, and consists of a fuse in series with a gap which is instantly closed

when a short-circuit, caused by an arc-over or ground, occurs. The arc is thus shunted until the fuse blows, which gives sufficient time to allow the arc to extinguish itself. For a single-phase, two of the fuses will blow, and for a three-phase short-circuit, all three fuses. If the trouble does not clear itself or if there is a dead ground, of course, the main oil-circuit-breaker will finally disconnect the entire circuit as usual.

663. Peterson Earth-Coil :—This is a reactance coil between the neutral of the system and the ground, the reactance being proportioned to neutralise the capacitance between the overhead transmission conductors and ground. It serves as an arc suppressor ; its operation being based upon a tuned electric circuit. Each line conductor has a capacitance, of the same value connected to the ground. The reactor is adjusted to produce an anti-resonant condition in the circuit composed of the line capacitance to the ground ($3C_g$) and the reactor. An anti-resonant circuit of inductance and capacitance in parallel has infinite impedance. Hence, any arc to ground (Fig 10·89) instead of being in series with the low capacitive reactance of the lines to ground, $1/(3C_g\,\omega)$, is in series with a very high impedance. The resistance component of the impedance cannot be eliminated, but it is small. Another explanation of the operation of the earth-coil is that the capacitive current from lines to ground and the inductive current in the reactor are nearly opposite and equal, so that the earth current must be nearly zero. It can be shown that the inductance of the Peterson-coil should be $L = 1/(3\omega^2 C_g)$ henries. Where ω is 2π times the line frequency.

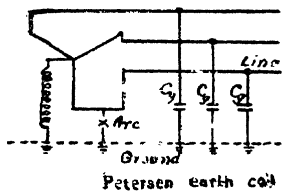


Fig. 10·89

The Peterson-coil is very limited in its application. If used on a line where different sections are switched, it will necessarily lose its effectiveness, because of the changes in the capacitance of the system to ground. It is found that the coil produces surges on switching,

hence, it is found advantageous to operate with the circuit over-tuned (23 per cent. too much inductance) to reduce oscillations. In Europe, the practice is to use an iron core. In the normal unsaturated condition the circuit is untuned with an arc discharge, the iron becomes saturated, bringing the circuit into the anti-resonant condition.

664. The Total Capacity to Earth on any system may be calculated approximately, but actual tests do not always confirm calculated values. The equation by which the capacity currents from any conductor or conductors are calculated is as follows :—

$$I_c = 2\pi KfE\, 10^{-6}$$

where, I_c = capacity current,

K = capacity in micro-farads,

f = frequency, and

E = virtual voltage between conductor and earth.

665. Earthing of Neutrals :—The question o earthing the neutral point or some other point of the system is of primary importance. It should be understood that the majority of the faults which occur on any system is faults between conductors and earth. If protective gear is to function at all, it is essential that any fault current from the conductor to earth should have an adequate return-path to the system, as otherwise, the current taken by the fault may be limited to such an extent as to prevent the apparatus from operating. It therefore becomes necessary to provide a path from the neutral or some other point of the three-phase system, or from some point on a single or two-phase system to earth of sufficiently low impedance to enable the protective gear installed on the system to function correctly.

On large system, there may be no necessity to provide any direct earth, since the path provided by the total capacity and leakage on the system may have a sufficiently low impedance to ensure operation of any protective gear which may be installed.

On any systems the total capacity between the conductors and earth may be considered as equivalent to single capacity connected between the neutral point of a system and earth, and also the sum of the leakages of the system may be considered as equivalent to a single resistance connected between the neutral point and earth. If the impedance of these two paths in parallel is too great to allow a current to pass through a fault of a magnitude sufficient to cause operation of the most heavily set circuit-breaker on the system, it becomes necessary to decrease the impedance between the neutral point of the system and earth, and this is generally done by *using some form of the earthing resistance.*

666. Advantages and Disadvantages of Earthed and Insulated Neutral of High Voltage Machines :—

Insulated Neutral.	Earthed Neutral.
1. The earth-fault on one phase of a 3-phase star connected system cannot stop the supply as it can neither short-circuit nor increase the leakage current too much.	1. The earth fault on any one phase will cause a short-circuit, and can therefore operate the overload or selective relay thus stopping the supply and generation.
2. When any one of the phases is grounded due to fault, the voltage strain on the insulation of the other healthy phases will increase to $\sqrt{3}$ times that of the voltage between line and neutral.	2. The earthing of any one of the phases causes discontinuity before the voltage strain increases.
3. The more voltage strain on the healthy phases will try to deteriorate their insulation and develop fault on the healthy phases. This afterwards causes short-circuit and can operate the relay.	3. No effect on healthy phases.

Insulated Neutral.	Earthed Neutral.
4. The earth fault on one of the phases is rarely in the form of a definite connection to earth. It is generally in the form of an arc, being shunted by the capacity of the phase conductors and so unstable. The arc is never continuous. The high voltage charge is sometimes added to and at other times subtracted from the normal voltage of the machine. When voltages are added, the arc begins, and it extinguishes when they oppose. The abnormal voltage strain on the insulation due to arcing grounds spoils the insulation as a whole.	4. There is not much possibility of arcing grounds in the earthed neutral system.
5. If the insulation of the phases be designed for $\sqrt{3}$ times the phase voltage, the strain on the insulation is decreased. The cost of the machine will then be more	5. Since the voltage strain on the insulation does not increase more than phase voltage, the cost of the machine is less.
6. The interruption of service is less at the cost of the machine.	6. The interruption service is more, but saves the machine.

667. Methods of Earthing :—

There are two at present :—

(*i*) Reactance method,
(*ii*) Resistance method.

(*i*) **Reactance Method** :--This is simply inserting . a reactance in the neutral to the earth bar. A 10°/o reactance *i.e.*, whose voltage drop will be 10°/o of the total voltage, is used. But the most recent practice is to add a reactance of value $2\frac{1}{2}$ to 6°/o and a resistance one.

(*ii*) **Resistance Method** :—The neutral is grounded through a resistance and this to some extent overcomes the disadvantages of grounded systems. The resistance must be of such a value that it will limit the current which would flow with a ground on the system to about 2 or 3 times the normal full load value of the highest capacity feeder. This will also permit a sufficient current flow to assume a definite selective operation of the relays. And in case of an arcing ground such a dynamic current would tend to make the ground permanent and the arc quite steady thus preventing high frequency oscillation from being set up. Such oscillations are set up when an arc is continuously interrupted and reformed, and may be very dangerous as they will super-impose on one another resulting in very high voltages. With a sufficient current flowing through the accidental ground, the arc will usually be quite free from oscillations and the breaker will usually trip before a short-circuit between phases occurs in the line.

When two or more units are grounded at a time, circulating currents would probably flow between them and that is the reason why only one unit is connected to the ground bus even when two machines run in parallel.

Earthing the neutral at different points in a system is objectionable from that point of view of providing a return circuit for triple harmonies and its odd multiples which interfere with the telephone communication. (Figs. 10·90 and 10·91.)

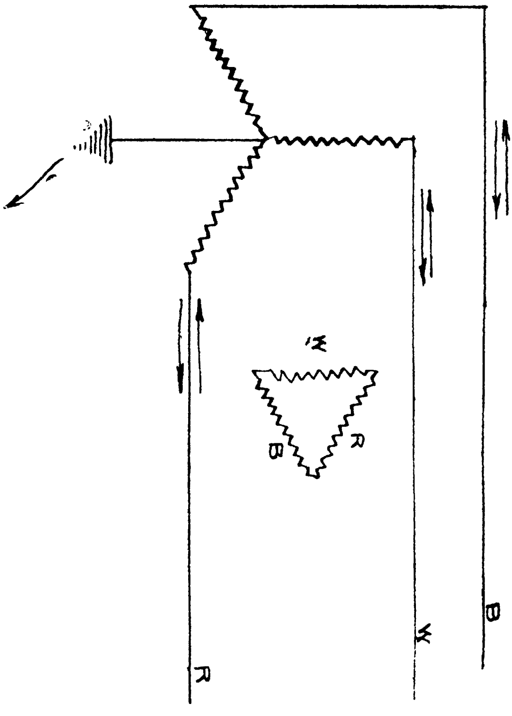
Example 11. The largest neutral resister in a station, all of whose neutrals are grounded through resisters, is rated at 5,000 amps. for 2 minutes. What size of ground bus should be used, if its joints are to be bolted ?

Solution.—

Using Currier and Rhodes formula for the area of the ground bus :—

$$
\begin{aligned}
A &= 10{\cdot}5\, I \sqrt{S}. \\
&= 10{\cdot}5 \times 5.000 \sqrt{2 \times 60} \\
&= 576000 \text{ Circular mils.} \\
&= \frac{576,000}{1,273,237} = {\cdot}454 \,\square''
\end{aligned}
$$

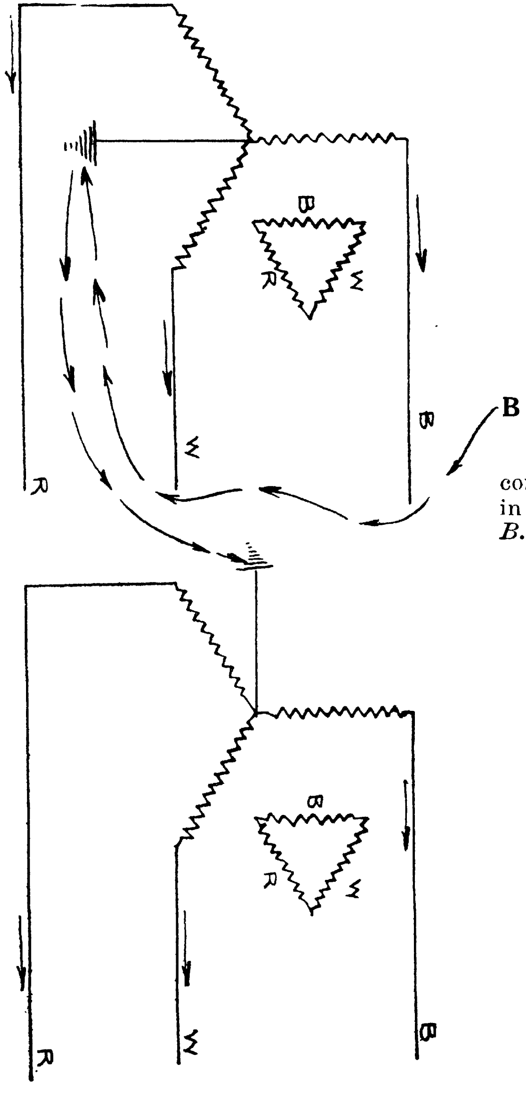
Hence a bar $2'' \times \frac{1}{4}''$ can be used, giving an area of $\frac{1}{2} \square''$



A

The current goes from *A* Fig. No. 10·90 to *B* Fig. No. 10·91.

Fig. 10·90



Current comes from A in Fig. 10·90 to B.

Example 12. Two 1,000-K.V.A, 2,300-volt generators of a power-station operate with solidly grounded neutrals (one neutral being grounded at a time). Find the size of the ground bus.

Solution.—

Using Currier and Rhodes formula,
for the given conditions

$$A = 114{\cdot}5\ I'$$

Total normal current $I' = \dfrac{2 \times 1{,}000}{2{\cdot}3\sqrt{3}} = 503$ amps.

$$A = 114{\cdot}5 \times 503 \text{ circular mils.}$$

$$= \frac{114{\cdot}5 \times 503}{1{,}273{,}237} = {\cdot}454 \,\square''$$

$\therefore$ As in the above case $2'' \times \frac{1}{2}''$ bar can be used, or, if we like, $2'' \times \frac{7}{32}''$ bus can also be used.

668. Earthing of Metal Parts :—It has three objects:—(1) Safe-guarding of employees, (2) Protection of circuits and apparatus and (3) Operation of relays.

Equipment to be grounded includes the following:—

Switchboard frames and supports.
Instrument and meter cases.
Non-current-carrying metal parts of switchboard devices with which the attendant may come in contact.
Transformer frames and cases.
Oil-circuit-breaker frames and mechanisms.
Rheostats.
Generators, motors and starters.
Instrument-transformer secondaries, at the transformers.
Lighting-transformer neutrals.
Steels supports and structures.
Bases of disconnecting switches and fuses, especially when mounted on masonry.
Lightning arresters. These should have individual grounds with straight, direct ground connections.

669. Conditions where Earthing is Necessary :—

(*a*) For all pressures of supply, earthing of metal objects other than the conductors shall be effected in the following cases :—In bath-rooms, lift shafts, near running machinery, and in all places where even a slight shock might lead to serious accident. All exposed metal liable to become alive, or situated so that there is risk of contact with earthed metal, shall be earthed. The metal sheathings of cables shall be earthed.

(*b*) Where the pressure of supply exceeds the limits of extra low pressure, any damp plaster, concrete, or metal shall be earthed which is liable to become alive and touched by a person making contact with earth. All metal conduits shall be earthed.

670. Position of Metal in Bath-rooms :—All exposed metal liable to become alive shall, in addition to being earthed, be placed out of reach of a person standing in the bath. Lamp-holders shall have their exposed metal parts efficiently earthed ; or alternatively, all parts liable to be handled when replacing a lamp shall be constructed of insulating material.

671. Considerations in Earthing :—

(*a*) The combined resistance of the earthing lead and system should be low enough to let enough current flow to operate the fuse or earth leakage trip.

(*b*) Water pipes used as an earthing system shall have metal joints throughout.

(*c*) Pipes conveying gas or an inflammable liquid shall not be used as an earthing system.

(*d*) An earthing lead shall be of high conductivity copper protected against mechanical injury and corrosion of not less than 0·0045 sq. in. (7/·029 in.) for the main connection. For flexible cords 0·0048 sq. in. and smaller, earth lead to be the same size as live conductors.

(*e*) All connections of the earthing lead shall be easily accessible.

(*f*) All domestic appliances, whether portable or fixed for pressures exceeding 100 volts direct or 30 volt alternating current shall be provided with a terminal or other suitable means for earthing all exposed metal.

672. Ground Detectors:—Ground detectors are made for single and poly-phase circuits and are enclosed with a cast or steel metal case.

Operation :—In the case of single-phase instruments when properly connected, if a ground occurs on one side of the line, the needle will incline towards the side of the instrument, to which the grounded line is connected. Fig. 7'14, p. 560. A full scale deflection indicates a comparatively low resistance ground. The three phase ground detectors have three needles which point towards the centre of the instrument when no ground exists When a ground occurs on one of the three lines, the two needles adjacent to the segment connected to the grounded line are deflected towards that segment should a ground occur on two lines will be deflected towards the one having the lower resistaance ground and the two remaining needles will be deflected towards the grounded segments.

673. Light-Sensitive Cells:—In a rapidly increasing number of cases, protective devices are controlled or actuated by some form of light-sensitive cells. The electrical properties of several materials, as selenium, are markedly affected by exposure to light ; and certain substances, as the alkali metals, have the property of directly converting light into electric energy The devices containing the active light sensitive material, arranged to be connected into an electric circuit, are usually called *cells* ; or more specifically *light sensitive cells, photo-electric cells, photo electronic cells*, and *photo-voltaic*

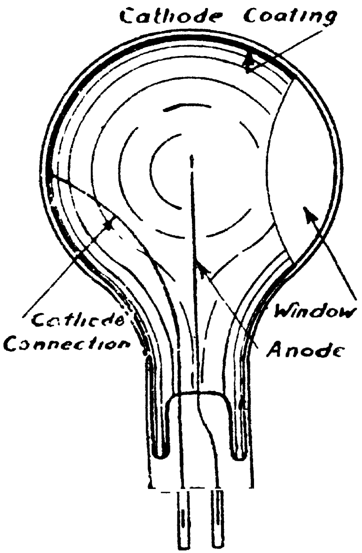


Fig. 10'92

cells. Under the general term of light-sensitive cells, there are three groups or types based on three different physical processes.

1. Photo-electric or Photo-electronic cells.
2. Photo-electric or Photo-voltaic cells.
3. Light-sensitive or photo-conductive cells.

In *the photo-electric or photo-electronic cells* the active materials are the alkali metals, particularly cæsium, potassium, sodium and rubidium, or some of their compound. A cross section of a typical photo-electric cell is showu in Fig. 10'92. On the inside surface of a glass bulb a layer of silver is deposited, covering the greater part of the surface but leaving a clear section or window through which the light beam may reach the sensitive material. The inside silver surface is then coated with a very thin layer of cæsium or potassium anhydride, some other light-sensitive substance. The sensitive film is extremely thin, in some cases, approaching to a single layer of atoms over the silver surface. An electrode connected to the middle part of the silver coating, forms the anode. Under light exposure the sensitive film, covering the silver coating, liberates or emits electrons thereby generating a potential difference between the cathode and the anode. The current produced by the ordinary photo-electric cell is small, only a few micro-amperes ; but the operating characteristics, as regards sensitivity, speed of response, reproducibility and direct proportionality of the current to the light intensity, are highly desirable for many forms of control and protective appliances.

The *photo-voltaic cells* have the appearance of an electric battery, in which the two electrodes are immersed in an electrolyte. In one form cuprous oxide and lead form the electrodes, and a solution of lead nitrate the electrolyte. On exposing the cuprous oxide to light, voltage is generated in the cell. Larger currents are produced than by the photo-electric cell ; the out-put being approximately 4 milli-amperes per sq. in. of electrode surface. In the *third type of light-sensitive cells* exposure to light greatly varies the resistance of the active element.

Selenium is the material generally used in photo-conductive cells. The change in resistance of the cell in the dark or exposed to light may be more than, 10:1. Sufficient current to operate relays may be passed through selenium cells.

The applications of light-sensitive cells are very numerous and may be classified into several groups, as control of processes, safety devices, sorting of materials on a colour basis, evaluation and quantitative measurements of light intensities and indicators of sequeuce of events or change in conditions.

CHAPTER XI

LOCALISATION AND REMEDY OF TROUBLES

674. The following Troubles generally occur in Electrical Machines :—

I. GENERATOR TROUBLES.

(1) Generator fails to generate.
(2) Sparking.
(3) Heating—(*a*) of Electrical Parts.
(*b*) of Bearings.
(4) Noisy Operation.
(5) Wrong Speed.
(6) Voltage of Generator too high or too low.

II. MOTOR TROUBLES.

(1) Motor refuses to strat.
(2) Motor runs in the wrong direction at Low Voltage and on Heavy Load.
(3) Motor starts suddenly at some particular Stud of Starter.
(4) Overheating of Starter.

III. SPECIAL TROUBLES IN A. C. MACHINES AND THEIR REMEDIES.

(1) Generator not developing normal E.M.F.
(2) Motor stops or fails to start.
(3) Poly-phase Induction Motor runs single-phase.
(4) Synchronous Motor fails to reach Synchronous Speed.
(5) Troubles with Wound Rotors.
(6) Faults common to all kinds of Motors :—

(*a*) Rotor fouling Stator.
(*b*) Hot Bearings.
(*c*) Stator faults.
(*d*) Other faults in windings.

(7) Troubles in three-phase motors with wound-rotors.
(8) Defects in Compensator or Auto-starter switch.
(9) Motor stops when particularly loaded.
(10) Bearing faults, Oil leakage, etc.
(11) Improper End-play of Rotor.
(12) Flashing over Collector Rings, or at End Connections of Field Coils in Starting Synchronous Motors.
(13) Inspection of A.C. Motor Installations.

DYNAMO OR GENERATOR FAILS TO GENERATE.

675. Generator Fails to Generate :—

Note the General Rules :—

Series Dynamo.— It must have closed circuit of a definite resistance and it should be run at a certain speed.

Shunt Dynamo.—It must have light or no-load and certain minimum speed.

Compound Dynamo.—Similar to shunt, best to short-circuit series winding, or excite by fuse wire across terminals.

Note :—Shunt and Compound Dynamos require time to build up their shunt field coils.

676. Faults Due to Field :—

Cause (1).—*Residual magnetism too weak or destroyed, due to* :—

(*a*) Vibration or jerk.

(*b*) Proximity of another machine.

(*c*) Earth's magnetism.

(*d*) A strong current through the armature, when there is little or no field current, tends to neutralise or reverse the field-magnetism, owing to the back ampere-turns.

(*e*) Accidental reversed current through shunt or series field coils, not enough to completely reverse magnetism. The complete reversal of the residual magnetism in any dynamo does not prevent it from generating, but will make it set up a current of opposite polarity. Sometimes reversal of residual magnetism may be very objectionable, as in case of charging storage batteries ; but although the popular supposition is to the contrary, it will not cause the machine to fail to generate.

Cases (*d*) and (*e*) are likely to occur with self-exciting D. C. generators working in parallel, or in conjunction with a storage battery, but not in the case of a single machine.

Symptom.—Little or no magnetic attraction when the pole pieces are touched with a piece of iron.

Remedy.—Pass a magnetising current from another machine or battery through the field. If this fails, send current in the opposite direction since the magnets may have enough polarity to prevent them from building up in the direction first tried

Move the brushes backward to make the armature magnetism assist that of the field. Turn machine around or change its polarity so that the magnetism which the earth or the adjacent machine tends to induce is in the same direction as the residual magnetism.

Dynamos should be placed with their opposite poles towards each other, and the north pole of a machine should preferably be placed towards the north, but the earth's magnetism is hardly strong enough to reverse or even materially affect the residual magnetism.

If the pole-pieces of a bipolar machine attract the same end of the magnet, then both of them are of the same polarity, whereas, they should always be of opposite polarity. In multipolar machine, this test should be applied to consecutive pole-pieces.

Reverse the connections of half of the coils to make the polarity of the pole-pieces opposite. The pole-pieces should be alternately north and south.

Cause (2).—*Reversed connections or reversed direction of rotation:—*

Symptom.—When the machine is running, pole-pieces do not attract a piece of iron. The application of external current does not, in this case, make a dynamo generate as in the previous case.

Remedy.—(*a*) Reverse either the armature connections or the field connections, but not both.

(*b*) Shift brushes through 180° for two pole, 90° for four-pole machines, etc.

(*c*) Reverse direction of rotation. After each of the above changes the field may have to be built up with a battery or other current.

Cause (3).—*Reversed Field :—*

Shunt dynamo.—Reversed field current due to armature reaction on dead short-circuit.

Series and Compound.—By motoring current on shutting down, passing in reverse way through series field coils.

Remedy.— (Shunt)—separately excite in correct direction, and try.

(Series)—separately excite in correct direction.

(Compound)—if in parallel with others, equalising switch will correct matters automatically.

If a separate machine, it may excite incorrectly for bus-bars; change over shunt field leads to cause machine to excite, and main leads to bus-bars to ensure correct polarity.

Better use current from outside source to excite shunt field correctly, series field coils being short-circuited when running up.

Cause (4).—*Field coils opposed to each other :—*

Remedy.—Pass a current from another generator or battery and test with a magnetic needle.

Cause (5).—*Open circuit:*—due to (1) Broken wire or faulty connection in machine. (2) Brushes not in

contact with commutator. (3) Safety fuse blown or removed or circuit open. (4) Switch open. (5) External circuit open.

Remedy.—Search out the fault and repair.

Cause (6).—*Break in field circuit* :—

Remedy.—Make new joint. If the break is not easily found, disconnect at terminals and separatly excite Test whole current and each coil separately.

"*Flying*—Grounds," "Flying Short-circuit" and "Flying Open Circuits" sometimes occur in armature windings. These are intermittent troubles which may assert themselves when the machine is hot, after running underload, and its component parts expanded. Then, when it cools, the trouble may automatically correct itself. Sometimes the reverse condition occurs, that is, the fault will be present when the machine is cold, but will be temporarily corrected when it is hot. Furthermore, centrifugal force due to the rotation of the armature may be a factor in the situation, in which case, the defect may be present when the armature is stationary. Obviously, such troubles are very difficult to locate. About the only way to localise them is to run the machine until the defect has "burnt itself out" or otherwise rendered its presence sufficiently evident that it can be located by the usual testing methods described above.

Cause (7).—*Loose field contacts* due to loose nuts at connections.

Remedy.—Examine all field contacts at brushes and between individual coils, clean, if dirty, with sand-paper, tighten up all bolts and screws.

Cause (8).—*Break in shunt regulator or lines* owing to burning of regulator contact or bad contacts at studs or in lines.

Remedy.—Test whole circuit for continuity, turn rheostat arm until continuity is attained, if possible, to locate break in coils or bad contact stud.

. If regulator be correct, test line from machine terminal to regulator, and from regulator to shunt field connection for continuity.

Examine connecting points for broken wires held together by braiding.

Cause (9).—*High resistance in field circuit* :—(Shunt machine)—Too much resistance in rheostat or bad contact between brushes and commutator or no contact.

Remedy.—Cut out all resistance in field rheostat until machine excites, watch pilot lamp, regulate carefully, then re-insert. Examine brushes for free movement, make necessary spring adjustment.

Cause (10).—(Series machine)—*All current passing through diverter. Field coils cut out.*

Remedy.—Adjust diverter to send current through field coils.

Cause (11).—*Short-circuit in the machine or external circuit or field winding due* to oil, moisture or mechanical injury shown up by sparking at particular set of brushes and excessive heating of some field coils.

Symptom.—Magnetism weak but usually perceptible.

Remedy.—Clean all parts and test for short-circuit for removing the fault. A lamp socket, etc., may be short-circuited or grounded and prevent building up shunt or compound machines.

677. Faults in Armature :—

Cause (1).—*Short-circuit in winding.*

Remedy.—Run up for a short time and locate hot or smoking coil on armature core. If run for a long time, the coil will be burnt out. Remove copper dust, solder or other metallic contact between commutator bars. See that clamping rings are perfectly free, and insulated from commutator bars; no copper dust, carbonised oil, etc., to cause an electrical leak.

Test for cross connection or short-circuit, and if such is found, rewind armature to correct the fault.

See that brush holders are perfectly insulated. No copper dust, carbon dust, oil or dust, to cause an electrical leak.

Pick out mica between segments to clear away short-circuit between segments. If remedy is impossible

in this way, coil must be replaced. In case of emergency, cut through faulty coil at pulley end of armature and tape up the two ends, leaving the coil in place. Bridge the two segments at the commutator with a bridge piece across, large enough to carry the full armature current; the machine will run satisfactorily until the coil can be replaced.

Cause (2).—*Short-circuit between sections through Core*, probably due to mechanical fault during building or transit.

Remedy.—Test for continuity between commutator and shaft as usual; the two coils in contact with the core will short-circuit a set of windings. Unless the fault can be found and the points of contact be insulated, rewinding is the only cure

If the sparking points are found between coil and core, a piece of mica will remedy the fault.

Generally, the coils should be disconnected from commutator, and tested individually to the shaft for continuity to locate the faulty coils

Earth's fault in armature can only be present when the machine has been running for some time.

Cause (3).—*Contact between Expanded Parts of machine*:—When the machine cools down, contact is broken and renders location of the fault difficult.

Remedy.—Run the machine until the fault either burns out or its location becomes possible.

Cause (4).—*Breaks in Armature Circuit* due to vibration, heat melting solder at commutator connections with coils.

Such faults are generally found at the lugs or risers where the armature coils make contact with the commutator. The position is easily located by deeply burnt and pitted segments on either side of one or two segments, according to whether one or two contacts are broken.

Remedy.—Bridge the break temporarily by staggering the brushes, until machine can be shut down (to save bad sparking), and then repair.

Shut down machine if possible, and repair loose or broken connection to commutator bar.

If coil is broken inside, rewinding is the only sure remedy and may be temporarily repaired by connecting to next coil, across mica.

Solder commutator lugs together, or put in a "jumper," and cut out, and leave open the broken coils. Be careful not to short-circuit a good coil in doing this.

Cause (5).—*Cross Connections*:—Armature winding reversed during repair, in which case the E. M. F. generated will cause polarity of machine to be reversed and will reduce field to zero.

Remedy.—(Shunt) Change over field leads to send current correctly through field coils, and change over leads to enable the machine to deliver correct polarity at bus-bars. These two operations might be performed by changing over main leads at brushes, but this might mean lengthening of one lead. Each coil should test complete without cross and no ground.

If possible, shift all brush-gear, through pole-piece without any disconnecting whatever.

(Series) Change over the field and main lead at the brush terminals.

(Compound) Reverse main leads at brush cross connection. In any case do not touch series or shunt field connections,

678. Faults at Brush-Gear:—

(1) *Bad Contact.*—

Cause.—Dirty commutator and burshes generally.

Remedy.—Examine commutator and brush surfaces, and see if excitation results by increasing the pressure on brushes for a short time to secure better contact.

(2) *Short-circuit.*—

Cause.—Generally metal and carbon dust and oil over the brushes causing short-circuit between brush gear through frame, and preventing current from flowing through high resistance field coils.

Remedy.—Clean brush-gear, especially insulating bushings. Test for short-circuit between brushes and frame with a detector.

If the brush is broken, the test will locate it.

(3) *Incorrect Position on Commutator:—*

Cause.—Incorrect position of brushes makes only part of the generated voltage available at the brushes, perhaps not enough to cause machine to excite.

Remedy.—Shift brushes to more correct position, allowing time at each change for machine to excite. When excited, fix brushes in the least sparking position.

(4) *Brushes not in proper Position.—*

Cause.—Excessive voltage between brush leads due to wrong position of brushes and weak field.

Remedy.—In this case the magnetism and voltage are increased by shifting the brushes, and the dynamo fails to generate any current whatever.

Adjust brushes to the proper position so that the trouble ameliorates or disappears.

679. Faults on Mains:—

(1) *Short-circuit.—*

Cause.—Short-circuit between the main switch and machine, or beyond the main switch. The effect is to blow out fuses and open circuit-breakers indicating presence of such faults

Shunt machine not excited, since all current produced passes through low-resistance short-circuit.

Compound and Series machines would show great over-load on ammeters, pull engine up, spark badly, throw belt off, or drop voltage.

Remedy.—If the fault is on line, locate by blown fuses, etc., and treat accordingly.

(Shunt).—Open main switch. Try to excite machine. If unsuccessful, disconnect leads to board at machine terminals, and test with lamp or voltmeter if excited. If successful, fault is between machine and switchboard. If it still does not excite, short-circuit is in machine itself, probably across brush-gear due to metal dust and oil.

Note.—A pilot lamp placed across machine terminals is a valuable adjunct to indicate excitation at machine when there is no voltage shown at bus-bars. It also

acts as a safety break for inductive shunt field circuit in all cases.

(2) *Open Circuit.*—

Cause.—Break in line, no load, bad switch contacts or blown fuses.

Remedy.—(Series) When unexcited, unless external circuit is connected :—

Test main switch contacts, putting fuse-wire across. If machine excites, this shows open circuit beyond main switch. If not excited, put fuse across machine terminals and run up. If machine excites, change line between machine and main switch.

If machine still not excited, test field circuit for continuity, examine terminals, and tighten all connections.

Always examine fuses carefully and see that circuit-breakers are not open.

680. Fault in Prime-Mover, Speed Low :—

Cause.—*Lack of Steam*, bad regulation, belt slipping, overload.

Remedy.—Neither shunt, compound, nor series machine will excite below a certain minimum speed, no matter whether load be heavy or light.

(Shunt and Compound) Increase speed beyond normal if necessary, keeping main switch open. As voltage rises, insert resistance in field rheostat to prevent excessive pressure and reduce speed to normal value.

(Series) A series machine is not much affected by this, for, with a certain minimum load, normal speed will nearly always cause it to excite. Since a series field builds up very rapidly, it is rather dangerous to increase the speed very much ; this may cause fuses to be blown or other damages done to the machine with a heavy load before the speed could be reduced.

681. Sparking :—

I. Sparking due to Brushes Themselves,

Cause (1).—*Bad Adjustment. Brushes not set equidistantly apart.*—Bad adjustment generally produces

bluish sparks, which increase or decrease according to position. If no change in the sparking is produced by moving the brushes, the cause is not due to bad brush adjustment.

Remedy.—If serious sparking occurs shut down the machine. Count the bars between brushes, measure the distance around the commutator and space equally. When running, move the rocker until one set of brushes at normal load is in sparkless position, then adjust others so that they are in the least sparking position.

Cause (2).—*Brushes not set at neutral points or exact points of commutation.* Rapid cracking sparks are visible at the edges of the brushes on heavy load, which rapidly produce flats.

Remedy.—Move the rocker back and forth slowly at normal load and voltage until sparking just commences. Then set and clamp in mid-way position. Give a small load on this position for a dynamo, and a small lag for a motor.

A badly designed machine will not have a sparkless position at any load Setting in best average position, or shifting brushes with load is recommended

Cause (3).—*Brushes not in line.*

Remedy.—Adjust each set of brushes until in line with shaft and square with commutator

Cause (4).—*Pressure on brushes incorrect.*

Remedy.—Test the actual pressure by means of a spring balance and adjust the tension until—

$$\frac{\text{Total pressure in pounds}}{\text{Brush contact area in square inches}} = 1\cdot5 \text{ to } 2 \text{ lbs. per sq. inch.}$$

Too great pressure produces grooves on the commutator, and too low pressure vibration and sparking,

II. Bad Condition :—

Cause (1).—*Not properly trimmed.*

Remedy.—Copper brushes require filing, clipping etc., to get rid of jagged edges. If there are more brushes per set, one may be removed for retrimming while the machine is on operation.

If the brushes are dirty, clean with alcohol, petrol or benzene to get rid of metal dust, carbonised oil, etc. : grind and reset carefully.

Cause (2).—*Bad contact at commutator, due to bad bedding.*

Remedy.—Set properly so that all the end surface of the brush is in contact. Clean commutator of oil and grit with benzol or soda, and bed afresh.

Cause (3).—*Bad fitting in the holders.* Brushes do not move freely, but stick in holders.

In this case, spluttering sparks are generally produced.

Remedy.—Lift and drop to test if the brush works freely under spring pressure. Smooth the outside of brushes and remove all burrs from holder by filing, so that there is a free up-and-down movement.

Cause (4).—*Vibration due to rough commutator, rough brushes, insufficient pressure.*

Remedy.—Smooth both brush and commutator surface and adjust tension screws and springs to secure light, firm and even contact.

Note.—Never use emery in any form for smoothing commutator or brushes.

III. External Causes :—

Cause (1).—*Over-loaded brushes.* Carbon brushes carry about thirty-five to forty amperes per square inch without over-heating.

Remedy.—Calculate the current taken per square inch of brush from the equation :—

$$\frac{\text{Total current in external circuit}}{\text{Total area of positive brushes}} = 35 \text{ to } 40 \text{ amperes.}$$

Reduce the load if the result exceeds this value.

Look at the ammeter when sparking just begins. If this indicates 50 per cent. overload, reduce the load, otherwise the overheating produced may damage the insulation of the machine.

Cause (2).—*Glowing and Pitting of Brushes.* This is due to too wide brushes generally. The sparks may

be invisible under the full length of the brush. These result in pitted surfaces. The effect may be also caused by the brushes being out of line; and is due to the heating effect of the commutating current in the coil short-circuited by the brush. This line current may be quite normal when this short-circuit takes place.

Remedy.—Set brushes in line and see that they do not cover above two segments. Move and set them in the least sparking position.

Cause (3).—*Chattering of Brushes.* This trouble may be accompanied by such serious sparking as to break the brushes sometimes. This annoying symptom always occurs with carbon brushes with box-guides.

Temporary relief may be effected by lubricating the commutator, but this is ineffectual and unpractical. Chattering is prevented by setting the brushes at such an angle that the angle between the medial line of the brush and the line joining it to the centre of the commutator is less than 10°, provided the brush trails on the commutator. A leading brush may often cause chattering and bad running if the direction of rotation be such as to cause the commutator to come against the brush. Such setting requires correction.

IV. Sparking due to Commutator Trouble :—

(1) *Bad condition of surface :—*

Cause.—Not smoothed off after last turning up, dirty condition of brush contacts and commutator surface owing to the presence of oil, or emery or glass particles.

Worn out and out of round. Brushes unsuitable. Armature having no end play.

Remedy.—If not too bad, grind with fine glass-paper and polish with crocus cloth while running normally at light load.

(2) *Rough, grooved, eccentric ridges :—*

Cause.—Excessive brush pressure will produce ridges. Emery or glass particles embedded in brush produce scours on the commutator and cover the brushes with copper particles which further tear the surface. With

high speed and rough commutator, brushes jump and chatter, producing sparking, which is further aggravated by excessive heating.

No end play of armature. Armature of every machine should have 1/16 to 1/8 inch end play when running, to wear commutator evenly and smoothly, and to allow the machine to run in the magnetic centre of field and armature cores.

Remedy.—If too bad, take the armature out of its bearings and turn off true in a lathe.

If rough, generally, file or grind with grind-stone or sand paper on curved block.

All grinding and smoothening may be done while the machine is running at a light load

After turning, always finish off the commutator with fine glass paper and then polish with a crocus cloth.

After the trial run, the resulting surface should be smooth, glassy in appearance, and dark brown or chocolate in colour.

(3) *Ring fire embracing the entire surface of the commutator :—*

Cause.—This is hot like the vivid flashes produced by a broken armature coil, and may be caused by the presence of conducting materials between segments, especially in slow-speed machines with under-cut micas.

Remedy.—Clean commutator, and brush out particles between segments.

(4) *High bars :—*

Cause.—Mostly due to bad workmanship. A high bar may cause singing.

Remedy.—Set down carefully with mallet and block of wood, if possible, then clamp tightly end nuts, or file, grind or turn true.

If only one bar is faulty, the position is easily located by the local sparking produced. If there are several faulty bars, the commutator wears rough generally.

(5) *Low bars :—*

Cause.—Bad Building. Generally indicated by local blackening and burning of segments.

Remedy.—Turning down the rest of the commutator simply is of little value.

Try to lift the low segment by a lever passed through a wire placed around commutator lug connection, or by means of a hand vice, and then tighten the clamping rings. In the first place, see if the binding rings are tight. If not, tighten these so that no further tightening would be possible when the machine was cold. Try tightening again after running for a time under ordinary load. Repeat this until the rings are quite firm ; then turn commutator true in lathe, polish and replace.

(6) *High mica :—*

Cause.—Due to turning with a blunt tool at a hig speed, wearing down of copper at a greater rate than mica, or to sparking itself.

Sparking due to high micas produces a general rawness all over the commutator surface. If this continues, the commutator becomes very rough, sparking and heating increase, which result finally in violent flashes from brush, blowing out fuses or opening circuit-breakers.

Remedy.—If after the commutator is smoothed off and polished, the sparking commences to appear again later, proud mica is probably responsible, and slotting should be taken recourse to.

Constant heavy loads aggravate the evil. But where intervals of light load intervene, *e.g.* on tramway and railway motors the roughening produced by proud mica often becomes smoothed.

(7) *Loose bars :—*

Cause.—Due to bad fitting, generally as in the case of high and low bars.

If the commutator is not properly settled when delivered, this evil soon makes its appearance when the segments are subjected to the various temperatures occurring in practice.

Remedy.—If close attention to the clamping rings fail to remove the trouble, rebuilding is the only remedy. Roughness due to a single irregular bar is detected by the local trouble near to bar and those corresponding to it around the commutator.

(8) *Flats :—*

Cause.—Due to low bar, overload, or any cause which produces periodic jumping of brushes and sparking at the same bar frequently.

This produces carbonisation on the bar causing high contact resistance, greater heating, more sparking, and increased flattening.

Flats may also be produced by an engine knock occurring at regular intervals with one particular set of segments under the brushes, or by a bad joint in a belt producing jumping every time the joint passes over the pulley. Amongst other causes, a bad segment, soft metal, etc., may be mentioned, in which case, replacement is the only cure.

On low speed machines, the blackened segments may seem to be the seat of sparking as they pass under the brushes. On high speed machines these will produce firing and flashing, which finally become so severe that the machine must be shut down.

Remedy.—The fault becomes worse, and recourse to temporary remedies are usually worthless.

Sand papering along the black segments parallel to the shaft aggravates the evil.

Attack the true fault, whatever it is. Remedy this, then grind or turn the commutator with properly shaped block, or a tool.

Polish the surface and slightly under-cut the micas.

V. Sparking due to Armature Faults :—

(1) *Short-circuited coils :—*

Cause.—One or more turns of the coil in contact due to defective insulation. Copper particles between commutator bars.

Faulty or broken down insulation of brush holders, or short-circuit between coils and armature carrying out sections of coils.

A faulty winding is located at once by a smell of burnt varnish and baked conditions of a particular coil.

A short-circuit at the commutator, may reveal itself with little effort at the commutator surface.

Remedy.—If not too far gone, the short-circuit may be easily corrected at lugs or risers or between segments.

If the coil be burnt out before the machine could be stopped, and the run is to be continued, the segments should be short-circuited by a bridge piece and the coil cut through and tapped at the pulley end of the armature in order to open-circuit the faulty winding. If due to ground, test and repair or rewind.

A faulty coil is easily detected by the drop-of-potential method.

(2) *Ground in armature* :—

Cause.—Caused by faulty insulation, due to damage or mechanical injury. One ground may not produce much harm.

Remedy.—Locate the grounds by a voltmeter or detector. If only one group, test by the drop of potential method. Megger test detects the presence at once, if test is made between any part of commutator and shaft. If the fault is not easily detected, rewinding is necessary.

To find the faulty coil definitely, the ends of the coils must be disconnected from the commutator and tested individually to core.

(3) *Broken circuit* :—

Cause.—Overload or violent flashings at commutator may have melted solder at lugs of commutator.

Break in coils is unusual. A break or bad contact is easily located by the "drop" method or by a continuity test.

Remedy.—See if there are badly burnt commutator-segments ; repair if only due to loose connection.

For temporary repair bridge the faulty segments leaving coil as before.

Staggering the brushes (by putting one forward and the other backward so as to bridge over the break) will also allow continuance of run until proper repair is made.

(4) *Crossed coil leads* :—

Cause.—Any wrong connection will manifest itself in the drop test by giving twice normal deflection between

two consecutive pair of segments, since two coils are connected in series.

The test made between the intermediate segments, will indicate ordinary result but reversed direction.

Remedy.—Locate, unsolder, and connect properly.

(5) *Reversed coil:*—

Cause.—Coil is crossed but connected to correct segments,

Remedy.—Pass a current through the commutator and locate by the drop test as in (4); or pass a compass needle around the outside of the armature: the needle will reverse its direction when passing over reversed coil. Trace out connections to faulty coil, and reconnect correctly.

(6) *Overload:*—

Cause.—Due to fault in mains or actual overload.

Remedy.—Reduce load.

(7) *Moisture:*—

Cause.—Damp situation, causing short-circuits and grounds.

Remedy.—Dry for several hours in an oven, or pass a small current through the armature, fields unexcited. If a dynamo, cause machine to develop a small current at a low voltage.

(8) *Eddy currents:*—

Cause.—Defective construction of the armature indicated by overload on prime-mover. Iron of armature core hotter than the coils upon it after a short run.

Remedy.—Rebuild and redesign, making lamination more perfect.

(9) *Friction:*—

Cause.—Hot boxes and journals affecting armature often causing it to take excessive current in case of motors.

Remedy.—Examine and reset bearings properly.

Note—When an excess of energy is taken by an armature for running free as a motor, whatever the cause, it is converted into heat by some defect. Hence,

the " free current " or " stray power " is the simplest and most searching test of efficiency and perfect condition.

(10) *Broken commutator lugs :—*

Cause.—Bending of shaft or want of alignment of bearings. Excessive vibration of slack commutator upon the shaft, especially in reversible motors.

Remedy.—The effect is the same as in broken armature coils. The obvious remedy is to straighten the shaft, reset the bearings, or fix the commutator tightly, if the trouble is due to this. In small machines, remedy is sometimes effected by using flexible wire connection between lugs and armature conductors.

Other effective measure is to substitute curved arms instead of the usual rigid straight ones, for the risers ; if the slackness of the commutator is due to a bad key-way, cut a new one at a different place and fit in a new key.

(11) *Too much current in armature :—*

Cause.—Due to overload, short-circuit, leak, or ground on the line. Excessive voltage on a constant potential circuit, or excessive current on a constant current circuit.

In the case of a motor, any abnormal friction due to the armature striking or rubbing against the pole-pieces, or the shaft not turning freely will have the same effect as an overload. (See similar troubles above.)

Remedy.—Reduce the load, locate and repair the short-circuit, leak, or ground on the line.

Decrease the size of driving pulley or increase the size of driven pulley. Decrease the strength of the magnetic field in the case of a dynamo or increase it in the case of a motor.

If excess of current cannot satisfactorily be overcome in any of the above ways, it will probably be necessary to change the machine or its winding. Too little resistance in the starter or controller will often cause a motor to start very suddenly and spark badly at first. In such a case, this resistance should be increased and properly adjusted.

(12) *Weak magnetic field :—*

Cause.—Due to broken or short-circuit or grounding of field coils. Reversed connections. Machine not properly wound, or without proper amount of iron.

Symptom.—Pole-pieces not strongly magnetic when tested with a piece of iron. Point of least sparking shifted cosiderably from normal position, due to relatively strong distorting effect or armature reaction. Generator fails to produce the full voltage or current. Low speed of shunt motors. All these may produce severe sparking at the brushes which must be avoided.

Remedy.—A break or short-circuit, or a ground is easily repaired, if external or accessible. If the trouble is internal, the only remedy is to replace or revive the faulty coil. Reversals of coils may be easily tested and corrected. No remedy for the last fault but to rebuild machine.

In the case of shunt machine if the voltage is too low on the circuit, or if the machine is run above the rated speed by weakening its field, it is likely to cause sparking.

To avoid sparking, voltage must be raised ; if impossible, reduce resistance of the field circuit by unwinding a few turns or substituting new coils. If due to high speed, strengthen the field and change the pulley of the driving or driven machine to suit the diminished speed.

This, however, is not applicable to ordinary types of shunt machine working at or near full torque. A reduction of load or current below the rated amount with corresponding field weakening is permissible without excessive sparking. In fact, the general rules concerning all commutator machines are, that the allowable current in the armature must be reduced as the field is weakened. (See "Fault due to field" and other similar troubles in preceding sections.)

(13) *Unequal strength of magnetic poles :—*

This might be treated as a special case of "weak magnetic field," but is sufficiently important and different in principle to demand separate consideration,

Cause.—Usually due to armature getting out of centre, or set closer to one or more poles than to the others. This fault sets up a back current in the armature which may rise considerably above the normal current, and produces bad sparking even with the external circuit open.

Occurs only in multipolar machines with parallel or multiple circuit winding, where there are as many paths for the current as there are poles.

Cannot occur in bipolar machines as the fluxes are equal for the two poles, and there is only one path through the armature. For this second reason, a multipolar machine with series or two-circuit winding (*e.g.* railway motor) is free from this trouble.

Remedy.—Test by measuring with a wedge if the armature is properly centred. This is often perceptible with the eye also. Correct by slightly shifting the bearings, or if convenient, the field magnet by putting in or taking out sheets of iron between the lugs or feet on the field-ring and the bed-plate. Another remedy is to vary the number of turns of wire in the field coils till the same flux is produced by each.

When due to too much wear in the bearings, it is preferable to renew the latter. To anticipate slight wear, the armature is sometimes set a little nearer the upper poles.

(14) *Vibration of the machine :—*

Cause.—Considerable vibration causes sparking which decreases as the vibration is reduced. Due to imperfectly balanced armature, pulley, engine knocks, bad belt or unsteady foundations.

Remedy.—Find out the true fault and apply proper corrections. Faulty construction. Revolving part may be taken out and balanced properly. If speed may be varied, vibaration can usually be diminished.

VI. Excessive Sparking in Interpolar Machines.

Cause (1).—Wrong interpole polarity.

Method of Detection —With low field excitation, examine the field polarity by a compass, the armature being removed beforehand.

Remedy.—In a motor proceeding in the direction of rotation, polarity should be $N-n$, $S-s$. In a generator, it should be $N-s$, $S-n$ etc.

Cause (2).—Interpoles not exactly over commutator zone.

Method of detection.—By inspection.

Remedy.—Adjust to the correct position if the poles are bolted to the frame.

Cause (3).—Brushes not set properly such that the coils undergoing commutation are under interpoles.

Method of detection.—Trace out following up coil up ends.

Remedy.—The usual setting is in the geometrical neutral. Set for minimum sparking under average load.

Cause (4).—Interpole air-gap too long or too short.

Method of detection.—See by means of the feeler guage the air gaps at every pole.

Remedy.—Adjustable when the poles are bolted to the frame, otherwise, weaken the interpoles strength by shunting the interpole winding.

682. Heating of Parts:—

I. Heating of Commutator and Brushes.

Cause.—Excessive current, short-circuits between segments, sparking, hot bearings, excessive pressure on brushes.

Remedy.—Reduce the load ; clean between commutator bars and slot a little if necessary ; clean the commutator surface of any oil or grit to secure good contact of brushes.

Examine, clean, scrape and polish the bearings, then reset properly.

Increased friction due to too great brush pressure decomposes carbon brushes covering the commutator with smut. This offers too much resistance and aggravates the heat.

Reduce spring tension and adjust for normal pressure. Lubricate with very little oil or vaseline.

II. Heating of Armature.

Cause.—*Excessive current in armature coils.* Short-circuit in coils indicated by burning insulation. Shut

down at once. Moisture in coils producing short-circuits and local currents ; indicated by the evolution of steam, or the machine taking considerable power to run free.

Eddy currents in armature core.

Crossed or reversed coils in the armature.

Heat conveyed from other parts. (See "Heating Field and Commutator.")

Armature unequally loaded, due to unequal strength of magnetic poles. (All these troubles are treated under "Sparking.")

Note.—The armature coils of an A. C. generator or synchronous motor are usually arranged in series, and as such, the effect of weakening or even omitting one of the field-poles is merely to produce a corresponding reduction in E. M. F. which may be easily corrected by increasing the strength of the other poles slightly. No short-circuiting or heating is likely to occur.

Operation at above rated voltage is indicated by high speed in motors, pilot lamps or voltmeter on dynamo.

Operation below normal speed, causes motors to take excessive current, or dynamo-fields to have to be over-excited to produce the rated E. M. F. Low speed also reduces the effective ventilation. A low power-factor, in the case of alternator, is indicated by the power-factor meter.

Remedy.—Voltage above normal is usually required to overcome excessive line drop, especially in A. C. transmission. This may be avoided by designing the line properly, or by introducing voltage boosting devices.

Operation below the rated speed requires an increase of field strength to make up the deficiency of speed. This causes heating and sparking, and may be remedied by adjusting the governor setting of the prime-mover, also calls for an increase of field strength to maintain the voltage at its proper value ; this causes heating in the armature core. The remedy is to raise the power-factor by reducing the inductane of the circuit, or by increasing the non-inductive devices, or connecting a super-excited synchronous motor to the line to draw a leading current.

An A. C. motor, put on a circuit of too high frequency, would evidently have excessive eddy and hysteresis losses, producing undue heating. Have the motor and frequency suited to each other.

III. Heating of Field Magnets :—

Cause.—Excessive current in field circuit due to high voltage or overload in case of compound machines. Coils too hot to be touched by hand.

Short-circuit in coils, or grounding through the core. Coils unequally heated. (See under " Sparking. ")

Eddy or Foucault current in pole-pieces. Pole-pieces hotter than coils after a short run.

Moisture in coils, causing low insulation resistance. (See under " Sparking. ")

Wrong connections. (See under " Sparking. ")

Too high or too low frequency in A. C. lines.

Remedy.—In the case of a shunt or seperately excited machine, decrease voltage at terminals by reducing speed or increase field resistance by winding on more wire, finer wire or putting resistance in series. In the case of a series machine, decrease current through fields by shunt, taking a layer or more wire off the field-coils, or rewind with coarser wire.

Coils may be connected in parallel and others in series by mistake. In the former case, all the coils will be excessively hot, and in the latter only the faulty ones. Test resistance of the coils to see if they are nearly equal. Disconnect and rectify connections, or insert resistance in series to reduce current to correct value.

Direct currents (except in machines, with open-coils armatures, used in arc lighting) rarely pulsate sufficiently to cause heating due to eddy currents. Corrected only by laminating field in A. C. machines and rebuilding.

In the case of induction motors connected to a high frequency line, the eddy current and hysteresis losses would be augmented resulting in heating of the magnetic circuit. With too low frequency, the stator (primary) winding of the motor will carry an excessive current. Temporary, for the first case, remedy would be to reduce the flux by decreasing the impressed voltage ; and for the

second to insert protective resistance in the stator connections. The machines should be rewound and rebuilt for the line frequency.

IV. Heating of Bearings :—

Cause (1).—Poor or insufficient oil. Defective feeds and rings.

Remedy.—See that plenty of good mineral oil, filtered clean, is provided in oil cups and reservoirs. Be careful that leakage along shaft, commutator or brush holder due to excess feed does not take place. Due to leakage, oil often fails sooner than the attendant expects. See that the oil rings are clean and work freely.

Renew oil about twice per year, but more often if it becomes dirty.

Cause (2).—Dirt or grit in bearings.

Remedy.—Wash out grit with oil while running with a thin oil or paraffin, clean up immediately and introduce good lubricating oil.

Warm soapy water may be used in place of paraffin with plenty of soft soap. See that excess oil does not creep along the shaft to commutator and armature coils. Remove the covers, clean and polish shaft and bearings. If badly scratched and hot when shut down, allow to cool slowly ; then clean, scrape, and polish shaft and bearings ; re-assemble, and see that all parts are free, and lubricate well.

Cause (3).—Rough journals or bearings.

Remedy.—Smooth and polish in a lathe removing all burrs, tool marks, and scratches ; wipe carefully, clean oil channels and refit. If the metal lining is very bad, remove old boxes and fit new ones.

Cause (4).—Journals too tight, due to newly fitted boxes or too tight bolts.

Remedy.—If the machine be running, slacken the cap bolts and put in liners, re-tighten till the run is over ; then scrape the bearings or fit in new boxes.

Cause (5).—Bent shaft, causing vibrations, armature to rub on pole-pieces.

Remedy.—Bend or turn true in a lathe, if only slight. If badly, best replace shaft by a new one.

Cause (6).—Bearings out of line, due to wear or bad alignment.

Remedy.—Loosen bearing bolts and line up until armature is in centre of pole-pipes, refit new bearings if necessary.

If bearing pillars are not in line, ream out the dowel and bolt holes, line up and secure in right position.

Cause (7).—Belt too tight, causing heat and elliptical wear by pulley bearings.

If due to heavy load, reduce the load so that belt may be slackened and yet not slip. Have larger and wider pulleys, and longer horizontal drive with lighter belt. Avoid vertical belts if possible. The slack side of the belt should be at the top. Too slack belts cause noises, winking lamps on the circuit.

Cause (8)—Armature near the pole-pipes on one side causing greater magnetic attraction on one side than on the other.

Remedy.—See "Sparking due to Armature Faults."

Cause (9).—Defective oil channels. Due to wear in bearings, oil channels often get shallower, and choked up with metal dirt. One-side wear in bearings may result in a machine having a large end pull, often causing the oil channels or the pulling side to close up.

Remedy.—Clean and make oil channels deeper. In case of ring bearings cut the channels from points near the top of the oil ring to the centre of the bearing, when there is a tendency to run dry at this point.

Cause (10).—Thrust or pressure of pulley, collar, or shoulder on shaft against one or both of the bearings.

Remedy.—If foundations are not level, test bed and bearings with spirit-level, and re-adjust if necessary.

Armature core may not run in the magnetic centre of the pole-pieces. While the machine is running, test by pushing at the end of the shaft with a block of wood if the armature moves away from the bearing at one end but not at the other. At the former, file or turn the bearing box or shaft collar slightly, so that the armature may be in the correct position with a little end play. In small machines, having no play, a cure may be effected by knocking the edges of the armature core discs a

little outwards towards the bearing, thus creating a tendency to pull the armature away from this end. This may also effect a cure in case the armature moves bodily along the shaft.

Pulley hub may rub on end of bearing; change the position of pulley on shaft until friction disappears.

If there is no end play, file or turn the ends of the boxes or collars on the shaft to provide this, or shift the bearing pedestal a little by filing the bolt holes in the base.

Belt may not be lined up with the shaft, but exerting a thrust upon it Line up the belt and shift the position of the pulley so that when the machine is running normally there is no end thrust, and the armature plays freely between its bearings.

V. Heating due to Bad Connections :—

Cause.—Abnormal current due to over-load or too small cables. High resistance due to loose and dirty contacts, absence of washer, bad soldering of lugs and thimbles.

Remedy.—Locate the right place of heat production and apply obvious remedy.

683. Noisy Operation :—

Cause (1).—Vibration due to revolving armature, field, pulley, or other moving part being imperfectly balanced.

Remedy.—Faulty construction, revolving part may be taken out and balanced properly. If speed may be varied, vibration can usually be diminished.

Cause (2).—Armature (see "Sparking at Commutator") striking pole-pieces, due to projecting coil or binder.

Remedy.—The points of contact are easily located. Bend or press down any projecting wire and secure with tie bands.

Cause (3).—Armature rubbing against pole-pieces, due to loose pole-piece or decentralisation of armature due to worn out bearings.

Remedy.—Tighten up the bolts, fixing pole-cores to yoke or pole-shoes to field-core. Reset bearings or pack up until air-gap is uniform all round. Filing out pole faces may be an efficient remedy.

Cause (4).—Shaft collars or pulley flange striking or rubbing on bearing box. This may be due to armature being out of centre; belt getting out of line; badly fitting boxes; loose or worn out bearing, etc.

Remedy.—See "Heating of Bearing."

Cause (5).—Rattling due to looseness of screws or other parts.

Remedy.—Examine and tighten up the loose parts and be careful to have all properly set up before run The trouble may be avoided by daily examining the various screws and other parts before the machine is started. A worn or badly fitted bearing might allow the shaft to make a rattling noise, in which case the bearing should be refitted or renewed.

Cause (6).—Singing and hissing of brushes. Due to dirty or sticky commutator and brush contact surface, or vibration of brushes.

Remedy.—Clean commutator while running, with a cloth dipped in paraffin and wipe dry. Apply very little oil or vaseline as lubricant. See if the brushes move freely under the action of the spring, adjust tension if necessary; or file the outside of the brushes and the inside of the box-holder with smooth file, and polish with fine sand paper.

Carbon brushes are apt to squeak at start or at low speed. This decreases at full speed and can usually be got rid of by slightly moistening the brush with oil, being careful not to leave any drops or excess of oil. Adjusting the length of the brushes or varying the brush pressure sometimes stop the noise. The machine should be run with little or no load until the commutator and brushes are worn smooth.

Cause (7).—Flapping or pounding of belt joint or lacing against pulley.

Remedy.—Use an endless belt if possible. If a laced belt must be used see that the jointed ends are cut square and tightly and evenly laced. A belt may strike the floor if slack side is at the bottom instead of at the top. With a slack belt, if the drive is too long, the two sides may strike against one another.

Cause (8).—Slipping of belt due to overload, too small pulleys or too slack belt.

Remedy.—This may be detected by excessively hot and highly polished condition of pulley surface. Reduce the load and tighten the belt; if possible, powdered resin may be put on the belt, to increase its adhesion; but it effects only a temporary remedy and is injurious to the belt, only to be adopted in an emergency. Special belt dressings which increase the adhesion and at the same time preserve the belt may be used.

Remedy the fault, do not simply alleviate it.

Cause (9).—Humming noises causing vibration of armature-core teeth or pole-shoe tips in machines of light construction and over-rated capacity. Due to bad construction and design.

Remedy.—No remedy except a radical change in design. Decreasing the magnetisation of the fields, or sloping the ends of the pole-shoes so that they are not parallel with the armature slots, may have some effect in reducing the noises.

Cause (10).—Humming due to alternating or pulsating current.

Remedy.—The sound is similar to that in the preceding case. This trouble is practically confined to the alternating current apparatus. The slight pulsations of direct current circuits due to the commutator, rarely produce an audible sound except in a telephone. The trouble may be minimised by mounting the machine so as to deaden the sound as much as possible.

Note.—It often happens that a noise really caused by an engine or other machine is wrongly located in the generator or motor. Listen carefully to the different parts to find out where the noise originates. A very sensitive plan is to hold a short stick or pencil by one end between the teeth and press the other end squarely against the several parts, thus ascertaining the particular part giving the greatest vibration.

684. Speed :—

I. Speed too Low.

Cause (1).—Overload on circuits, indicated by ammeter reading.

Remedy.—Reduce load. (See also "Sparking" and "Heating of Armature.")

Cause (2).—Short-circuit or ground in armature. producing heavy load not indicated on the ammeter.

Remedy.—See "Heating of Armature."

Cause (3).—Bad engine regulation, especially on heavy loads.

Remedy.—Adjust governor of engine to regulate properly, if possible, or get a better engine.

Cause (4)—Armature rubs against pole-pieces, or excessive friction in bearings causing overload of prime-mover.

Remedy.—Shut down and see if the machine turns freely by hand, or whilst shutting down stops suddenly. Treat trouble as for "Heating of Bearings and Noisy Operation."

Cause (5).—Weak magnetic field, due to high resistance in field rheostat, or a short-circuit in the field winding causing low voltage erroneously put down to low speed.

Remedy.—See "Sparking due to Armature Faults."

Cause (6).—Armature strikes pole-pieces

Remedy.—Treat trouble as for "Noisy Operation."

Cause (7).—Shaft does not freely revolve in the bearings.

Remedy.—Treat as for "Heating of Bearings."

II. Speed too High—

In the case of a Dynamo—

Cause (1).—Engine fails to regulate as indicated by excessive volts when the load goes off.

Remedy.—Adjust governor of the engine to regulate properly from no-load to full-load. If impossible, replace prime-mover.

In case of series motor, on a constant potential circuit, it should have its load positively connected or geared.

In the case of a Series Motor—

Cause (2).—Too much current, or sudden throwing off cf load.

Remedy.—If on a constant current circuit, pu in a shunt and adjust current to the proper value; use regulator or governor to control magnetisation of field for varying load.

If on constant-potential circuit, insert resistance and reduce current; include a proper controller in circuit so that resistance may be inserted and voltage at armature terminals varied according to load; use an automatic speed controller, if necessary. It is preferable to have the load of the motor positively connected or geared so that there is no danger that it will be removed.

In the case of a Shunt Motor—

Cause (3).—Field rheostat not set properly.

Remedy.—Re-adjust rheostat to control motor.

Other causes.—Supply voltage not suited to the motor; examine name plate, and see if in agreement with supply. Change the motor if necessary.

Weak field, due to low voltage at terminals, break short-circuit in field causing an excess armature current and blowing of fuses. Field and armature circuits may be connected in series in which case the motor starts correctly; but gradually reaches an excessive speed on light load, and slows down on excess of load, and no-load release coil burns out,

Speed too High or Low :—

Cause (1).—Field-magnetism weak.

This has the effect on a constant-potential circuit, of making a series or shunt motor run too fast if lightly loaded, or too slowly if heavily loaded, or even run backwards if the field is not excited at all, as, for example, when the shunt-field circuit is broken.

It makes a generator fail to "build up," or to give the proper voltage.

Remedy.—Treat as in "Sparking" under such conditions.

A single-phase motor stops if a break exists in its circuit. A two- or three-phase motor may, however, run single-phase at a lower load capacity if the circuit of one phase is broken. A two-phase motor or a three-phase circuit with a Y-wound stator under such conditions

would not start itself except by special means. A three-phase motor with delta-wound stator (the usual type) will generally start with one circuit open, but the starting torque and load capacity are reduced about 40 per cent.

Cause (2).—Frequency of circuit too high or low.

Remedy.—The speed of an induction or synchronous motor varies directly as the frequency; as such, machine must be designed for a certain given frequency. The revolutions per second equal to the frequency divided by the number of pair of poles. Speed is slightly reduced by the "slip" in case of an induction motor. It is possible, therefore, to vary the speed by rewinding or reconnecting the coils, so as to change the number of poles.

Cause (3).—Brushes not in proper position. In the case of interpolar motors, the speed increases very much if the brushes are shifted backwards (opposite to rotation) from the true geometrical neutral point, and falls too rapidly under loads if the brush is moved forward beyond the neutral position.

Remedy.—Move brushes to geometrical neutral point or until speed characteristics are same in both directions of rotation.

685. Voltage of Generator too High or too Low:—

Cause (1).—Speed too high or too low.

Symptom and Remedy—See "Speed too high or too low."

Cause (2).—Field magnetism strong or weak.

Symptom and Remedy.—See "Sparking," also "Dynamo Fails to Generate," various cases.

Cause (3).—Brushes not in proper position.

Symptom and Remedy.—See "Sparking," also "Dynamo Fails to Generate."

In the case of interpolar, direct-current generators, a marked compounding effect is produced when the brushes are securely placed midway between the main poles.

Cause (4).—Overloading of generator.

Remedy.—See "Sparking" and "Speed too high and too low."

Cause (5).—Short-circuits and reversals of armature coils.

Remedy.—See " Sparking."

Cause (6).—Open circuits, short-circuits, or reversals in field coils.

Remedy.—A break in the field will prevent rotor to " build up " and produce any voltage except the small amount due to residual magnetism. A short-circuit in the series field coils of a series or compound machine produces a corresponding reduction in ampere-turns provided the field current remains constant. In shunt wound or separately excited field-coils however, the current tends to increase in proportion to the decrease in the effective coils ; as such, the field strength and voltage remain unaltered. This condition, however, is not desirable, because the active field-coils carry excessive current. In multipolar machines (including practically all A. C. and large D. C. types) the cutting out of one field coil on account of an open or short-circuit, would not cause an increase in current likely to do harm. One reversed coil has obviously the same effect as the loss of two coils, the field resistance and current remaining unchanged. Hence to obtain the proper voltage the current has to be increased by means of the field-regulator. This increase must be twice as great as that required for one short-circuited coil. A short-circuit or reversal in field-coils is very objectionable fault in multipolar, multiple-circuit, direct-current machines (see also " Sparking and " Dynamo Fails to Generate ").

Cause (7).—Lagging current in alternators.

Remedy.—Direct and alternating-current generators (except compound or composite-wound ones) tend to fall in voltage with increase in load, this being due to armature resistance, inductance and reaction. The difficulty may be overcome if the field current is raised by cutting out resistance in the field rheostat. In alternating-current generators, however, for a given armature current, reaction and the weakening of the fields are much greater when the current lags, and therefore,

the fall in voltage and regulation required are correspondingly large.

Cause (8).—Wrong connections of armature coils in case of alternators.

Remedy.—An armature intended for Δ-connection would, if connected in Y-fashion, increase the line-voltage by about 73 % whereas, if the armature is connected in delta (though originally meant for Y-connection) the line voltage would be reduced by about 42%. Such an error is readily corrected by reconnecting the alternator terminals.

686. Excessive Current :—

Cause (1).—In case of a generator too much load of lamps or motor.

Method of detection.—By too high a reading of the ammeter than the capacity of the machine and also excessive sparking of dynamo brushes.

Remedy.—Cut out the excessive load.

Cause (2).—Short-circuit, leakage or ground in the external circuit.

Method of detection.—By excessive sparking of the brushes and heating up of the whole armature.

Remedy.—Locate and remove the leak or the ground.

Cause (3).—Short-circuit in the armature circuit.

Method of detection.—Heating of a particular coil than others.

Remedy.—Stop the machine, locate the coil and if entirely burnt, replace the coil.

Cause (4).—Ground in the armature.

Method of detection.—By heating of a particular coil in excess to others.

Remedy.—Locate the ground and re-insulate the coils that are defective.

Cause (5).—Due to excessive friction in the bearing or due to armature striking poles. In general, this slows down the machine.

Detection.—By sparking of the brushes. By the noise of the armature striking while running.

Remedy.—File away the pole pieces or recentre the armature. Clean the oil journals or refit the bearings.

Belt of Dynamo slips when loaded.

Cause (1).—Belt loose or glazed.

Remedy.—Tighten the belt by moving the machine on the rails (as is done on the test room set). If this is not possible the belt is shortened. A glazed belt is treated with resin.

Cause (2).—Machine overloaded or bad alignment of the shaft bearings.

Remedy.—Check the load current of armature, investigate the condition of shafting and possibility of overload cause.

Cause (3).—Driving pulley on motor and main pulley on shafting too small with result that the driving belt has not sufficient surface to grip.

Remedy.—Fit new driving pulleys to motor and shafting taking care not to alter the ratio of diameters if the speed of the driven number is to be the same.

687. D. C. Motor Troubles :—

(1) *Motor Refuses to Start* :—

(*a*) with switch closed and arm of starter over, only a small or no current at all passing :—

Cause (1).—Open circuit in armature, broken coils, indicated by burnt mica and segments.

Remedy.—Search out and repair, as for broken circuit, (see under "Sparking due to Armature Faults" etc.).

Cause (2).—Switch contacts bad. Starter arm not making contact at studs or controller fingers not making contact.

Remedy.—Test for signs of sparking and heating at contacts, dirty fingers, worn springs, etc. and treat accordingly

Cause (3).—Brushes not making contact on commutator.

. Remedy.—Clean commutator if dirty. See that the brushes are making contact and moving freely in their holders, especially when there is only one brush per pole.

Cause (4).—Bad, loose or broken connections at starter or machine terminals, due to dirt, etc., or actual break in wire close to socket.

Remedy.—Search out the fault and correct properly (see under "Heating" and "Sparking").

Cause (5).—Failure of supply.

Remedy.—This may be due to a temporary stoppage of current at the generating station, or on the line. Wait for some time and then try to run the motor by closing the switch, starter or controller for a moment. Test with an incandescent lamp or voltmeter whether current is flowing in the circuit. This will often determine the break in the circuit, if there is any.

Determine the particular cause and take necessary steps.

Cause (6).—Fuse melted.

Remedy.—Find out and replace fuse. This is a frequent cause of trouble, as a blown fuse is often difficult to trace. If in doubt, rewire.

Cause (7).—Wrong connection at starter.

Remedy.—If the connections for shunt and armature were interchanged, the armature current passing through the "no-load" release coil would heat it up and probably burn it out altogether in a short time. The motor would only run slowly.

In the case of Series Motor a broken field circuit may stop the operation altogether. Such a break is more often due to bad, dirty, or loose connections, rather than an actual break in the field winding.

(*b*) Fuses blowing immediately or as the arm of the starter is pushed over :—

Cause (1).—Overload due to excessive friction.

Remedy.—Test by running the machine without load. Examine the bearing for excessive friction by temperature test ; also friction between armature core and pole-pieces by observation or noise. Try moving the armature freely by hand with the belt off. (See under "Sparking, Heating of Bearings, and Noisy Operation").

Cause (2).—Excess current due to short-circuit in armature.

Remedy.—Poor insulation, dirt, oil and copper or carbon. See "Armature faults."

Cause (3).—Short-circuit in brush gear, due to copper or carbon dust and dirt over the brushes, or broken insulation at points where brush spindles are connected to brush rocker.

Remedy.—See "Generator fails to excite—faults at brush gear."

Cause (4).—Field winding of D. C Shunt Motor disconnected or broken with the result that full voltage is applied to the stationary armature when the starter is moved to the running position.

Remedy.—Test the continuity of the field winding with a portable battery and voltmeter and if the field winding is in order, look for other causes.

Cause (5).—Short-circuit in the motor or wrong connection in the motor starter. A short-circuit to the frame of some live part of the motor is equivalent to the short-circuit in the mains when one line of the mains is earthed. It is usual for one line of any type of power supply to be earthed.

Remedy.—If the starter connections are corrected—If they are found to be correct, the leads are disconnected at the motor terminals and the different sections of the motor are tested, the brushes being lifted from the commutator. The terminal and brush-gear bushings are examined to see that they are not short-circuited in any way. If the fault lies in the armature, it may be necessary to disconnect the wires from the commutator to find whether the commutator or armature insulation has broken down.

Cause (6).—Great overload indicated by excessive current, blowing out of fuses, or opening of circuit-breakers. A moderate overload generally reduces the speed of a direct or alternating current motor (except the synchronous type) to some extent, but an extreme overload will stop or "stall" any motor.

Remedy.—Open switch instantly, reduce load, replace fuses or circuit-breaker, and close circuit again just long enough to see if trouble still exists; if so, take off more load.

Cause (7).—Field too weak. This trouble mostly occurs in adjustable speed ("field weakening") motors.

Remedy.—Reduce resistance of the shunt-field circuit.

Other Causes (8).—If the machine runs correctly at light load, but with more load on, the fuses must blow, the mains to terminal "line" and armature may be interchanged at the starter. Short-circuit in the mains between the main switch and the motor, or one or more grounds in the machine may also be present.

Note on the three-wire (220-volt or 440-volt) *Systems of D. C. Supply* :—Several peculiar conditions may exist here which are as follows :—

(*i*) Generators on one side of the system may become reversed. In that case, both the outside wires are positive or both negative. Hence, a motor connected in the usual manner to the two outside mains will receive no current, but lamps connected across the middle or "neutral" wire and either of the outside wires will be lighted apparently with usual brilliancy.

(*ii*) If the blowing of a fuse, or some other cause happens to open a motor (200-volt) points beyond the break can still receive some current at 110 volts through any lamps connected across the "neutral" and open conductor on the same side of the break as the motor. The lamps will light up as soon as the motor is connected, but the latter will have little power unless the number of lamps is sufficiently increased.

(*iii*) If however, a break occurs in the neutral or middle wire, a motor connected to the outside wires will run as usual; but lamps on one side of the system burn more brilliantly than those on the motor, if the two sides are not balanced properly.

(*iv*) If one outside wire is accidentally grounded, a 110-volt generator, motor, or other apparatus also grounded and connected to the other outside wire, may receive 220 volts and be burnt out altogether. If the neutral wire is connected with the ground, which is generally the case, the grounding of either outside wire produces a short-circuit, blowing out the fuse or opening the circuit-

breaker, and thus saves the trouble. "Grounding the neutral" also makes it possible to limit (to one-half the total amount) the voltage-rise by an accidental grounding. Hence, it is always safe to ground the neutral to prevent the consequences of accidental grounding of either outside conductor with the neutral non-grounded.

(2) *Motor runs in wrong direction at low voltage and on heavy load.*

Cause.—Effect of overpowering series field on the shunt field.

Remedy.—First apply the principles of "reversal of rotation.

If a differential compound motor, short-circuit the series field, or reduce load until motor starts correctly.

In an additively wound motor, the series field may be opposing the shunt. In such a case, reverse the series field connections to brush-gear and main terminal respectively.

In both of these cases, the motor might run apparently in right direction on light load.

(3) *Motor Starts Suddenly* at some particular stud of starter.

Cause.—Break in starter coil, or bad contact at stud.

Remedy.—Clean or renew studs or fingers. Test coils and repair

(4) *Overheating of Starter*

Cause.—Excessive current in coils, due to overload or starter being too small for motor.

Remedy.—The starter should allow the motor to start slowly with load without excessive heating. If not, replace by one of larger capacity. If the fault appears suddenly, it is probably due to overload.

(5) *Output of Motor too low.*

Cause.—Voltage of mains too low. This causes the motor to run somewhat slower than it should. If the motor is connected to a main of much lower voltage than for which it is rated, the no-volt release of the starter usually operates.

Remedy —Test the mains pressure with a voltmeter, preferably with the motor running. There may be high

resistance contact in the system causing a drop. This will be located by the heat evolved from that part.

(6) *Motor Races.*—

Causes.—Unless the voltage of the main is higher than it should be, this condition can arise only when the motor load is light. Series machines race dangerously if a load is entirely removed. Shunt Motor races if there is a break-down in the field windings or when the fields are wrongly connected.

Remedy.—A Series Motor must not be used when there is a possibility of load entirely removed. In such cases, a compound wound field is employed. Check the polarity of the fields by a compass needle not holding it too close to the field magnets or the polarity of the needle will be reversed.

(7) *Machine overheats* :—(*i*) Overload—the load to be checked with ammeter (*ii*) Tight bearings, or bearings out of line, or bearings hot.—Overhaul the bearings and regulate lubrication (*iii*) Sparking (*iv*) One field coil of a bipolor machine short-circuited—test and rectify.

688. Main Defects in the D. C. Motor Starters are (1) Looseness of the spring ; (2) Contact studs near the magnet coil higher than the rest of the studs ; (3) Retaining of the magnetisation, in the iron holding the arm in position.

The effect of this defect is that the arm remains in the final position and does not come to its starting position. The remedies for this defect are—(1) To Change the spring ; (2) To file off the contact segments which are high, and lastly (3) To tin the keeper slightly with a soldering iron, thus placing a certain amount of reluctance in the magnetic circuit of the magnet and its keeper.

689. A. C. Machine Troubles :—In many cases A. C. machine troubles are similar to those of D. C. machines, and some of them, therefore, have already been treated somewhat fully in the sections dealing with the A. C. part under separate headings wherever it has been found necessary. Previous reference should

therefore be freely made to those as occasion arises. From another point of view, the A. C. machine is entirely of a different type from the D. C. machine, and as such, there are certain troubles, especially associated with it, peculiar to itself, and sufficiently important and different in principle to demand separate consideration.

690. General Classification of A. C. Troubles :—

(1) Generator—Fails to develop normal E. M. F., due to :—

(*i*) Faults in exciter.
(*ii*) Defects in stator winding.

(2) Motor—Refuses to start ; stops or runs at speed, due to :—

(I) Troubles with wound rotors :—

(*i*) Faults in starting switch.
(*ii*) Defects in rotor winding.
(*iii*) Faults at collector rings.

(II) Troubles with squirrel-cage rotors :—

(*i*) Winding fault.

(III) Troubles common to both kinds of rotors :—

(*i*) Defect in windings.
(*ii*) Faults at bearings.
(*iii*) Rotor fouling stator.
(*iv*) Overload.
(*v*) Wrong voltage and frequency.

(IV) Troubles with stator windings :—

(*i*) Winding fault.

(V) Troubles with compensator, or auto-starter :—

(*i*) Open circuit.
(*ii*) Wrong connections.

(VI) Troubles with bearings :—

(*i*) Leakage of oil.
(*ii*) Hot bearings.
(*iii*) Improper end-play of rotor.

(VII) Flashing over at collector rings.
(VIII) General Inspection of A.C. Motor installations.

691. Generator not Developing Normal E. M. F. :—

Cause (1).—Engine trouble. Bad regulation, lack of steam, overload causing speed low.

Remedy.—Set in order, if possible ; otherwise replace by a new engine. (See under "D.C. Machine Troubles.")

Cause (2).—Exciter trouble, indicated by ammeter and voltmeter readings.

Remedy.—The exciter may give low voltage and current, due to :—low speed, open or short-circuited shunt field, series field reversed and opposing shunt field, troubles in brushes and commutator, rheostat defective or not properly regulated.

Treat as in "D. C. Machine Troubles."

Cause (3)—Power factor too low, due to heavy load, or other external causes

Remedy.—Raise power factor by reducing load and removing other troubles. (See under "Heating of Armature.")

Cause (4).—Faults in stator winding, such as, short-circuit, open circuit, burnt- out windings indicated by excessive heating or smell of burnt insulation.

Remedy.—Bridge over short-circuited coil, cut through the coil at the pulley end of the armature, tape up the two ends, and continue to run until the coil can be replaced. (See "Faults in Armature," "Sparking and Heating.")

Cause (5).—Faulty instruments giving incorrect readings.

Remedy.—This may be detected from a knowledge of load conditions. If, in doubt, replace faulty instruments

692. Motor Stops, or Fails to Start :—

Cause (1).—Low voltage or wrong frequency.

Remedy.—Ordinary squirrel-cage type of induction motors are mostly affected by this trouble. This is because the torque of an induction motor varies as the

square of the voltage. Further, a motor of this type takes a huge starting current producing lug drops between the transformer and the motor, and thus aggravates the trouble at starting up. Its speed also varies directly with the frequency as in the synchronous motor.

Best thing is to provide a suitable motor for the supply.

Otherwise, use larger transformer or bigger line leads or both.

(See under "Heating" and "Speed High or Low.")

Cause (2).—Great overload.

If the load on the motor exceeds its maximum output, it may blow the safety-fuses, or open the circuit-breaker, and in their absence or failure, result, in a complete burn-out.

Remedy.—Excessive current flowing in the windings is often indicated by an increased humming of the motor.

A synchronous motor will carry its full load at synchronous speed. When the load is too great, the motor gets out of step and does not start, if not already running.

An induction motor carrying extreme overload may slow down and finally stop, or may refuse to start, if not already running.

Remedy.—Open the switch instantly, reduce the load and try starting again ; take off more load if necessary. (See under "D. C. Motor Troubles.")

Cause (3).—Open circuit, due to safety-fuse blown, circuit-breaker open, break in line-circuit, switch open, brushes not in contact with commutator or collector rings.

Indicated by the fact that if load is taken off, the motor still refuse to start, and yet armature can be turned freely by hand.

Remedy :—Open the main switch or circuit-breaker immediately, and examine fuses, circuit-breaker, switch, brushes and the line generally for break. Failing location, test windings of the motor for continuity with a

magnetic, or a cell and electric bell or by any ordinary test. Fine circuit being broken, a distinct humming may be given out by a motor showing that it is taking current single-phase, and yet will not start when turned by hand.

In the case of slip-ring motors with resistance in circuit, tests should be made for short-circuit or grounds in the starter.

Failing detection of faults by above tests, attention should be paid to the transformer or starting compensator, examining particularly for loose or broken connections, causing open circuit in one or more lines. (See " D. C. Motor Troubles " for other faults.)

Cause (4).—Open circuit in rotor windings.

Remedy.—In motors of the squirrel-cage type, in which the rotor bars are often soldered to the end short-circuiting rings, excess flow of current may sever connections at one or more joints by melting out the solder.

The remaining joints will therefore carry a heavier current, and in their turn heat up and melt out the solder, and become open-circuited, finally resulting in a shut-down. The joints should therefore, be brazed or welded together.

Bad joints should always be removed, as these prevent the motor from coming up to speed and produce unbalanced currents with excessive local heating.

A. C. machines are, as a rule, free from the danger of internal short-circuiting, because the armature winding is usually single-circuit. Such trouble is very likely to occur in D. C. armatures with multiple-circuit winding when a field-coil is cut out.

(See " D. C. Motor Troubles ").

Cause (5).—Supply cut off or power not reaching motor through faulty switches or disconnection of a wire. Brushes not bearing on the commutator.

Remedy.—With a voltmeter or a lamp of suitable voltage, first check the supply at the main switch, then if the mains are in order, test the voltage at the motor terminals with starter on the 1st stud. Do not hold the starter on the full 'on' position, because if the fault is an

intermittent one, it may suddenly clear itself, and the full voltage of the mains be applied to the motor. For the 3-phase supply each phase is tested separately.

693. Poly-Phase Induction Motor Runs Single-Phase :—

Cause.—Open-circuit in one line.

Remedy.—With one line or one phase of the stator winding open, poly-phase motors with delta-wound rotors (the usual type) are generally self-starting, but the starting torque is reduced by about 40 per cent. A poly-phase motor with a star-wound stator, under similar condition, would not start except by special means. Sometimes, induction motors are started without fuses in the circuit and blown fuses may escape observation. In such a case as this, the motor speeds up and thrown on the full-voltage mains, it will carry only about 70 per cent. of its full load with excessive heating.

Locate and set right any break, blown fuse, or open circuit-breaker.

694. Synchronous Motor Fails to Reach Synchronous Speed :—

Cause.—Short-circuit in field coils.

Remedy.—In this case, the motor starts, and comes up to a certain speed below that of synchronism, and cannot therefore be thrown on the full-voltage mains.

Test field windings for grounds.

Examine field circuit, specially at collector rings diverter, if any, used with the fields for short-circuits.

Rectify defect whatever it is, as under D. C. machine troubles

695. Synchronous Motor Fails to Start :—

When a Synchronous motor fails to start, the trouble is generally due to overload. In testing out for such a condition, the motor must be started light. If the operation is not satisfactory the load should be reduced. Poor starting may also be caused by reduced voltage, open or faulty connection in starting. An open circuit is usually shown by no current flowing in the particular

phase. An excessive current may be due to grounds. An excessive current in a Synchronous motor is a dangerous condition and the trouble should be instantly looked after. When a Synchronous motor is used for P. F. correction, overheating indicates an excessive current The machine, usually, can be operated temporarily by reducing the load or by reducing the amount of leading current, when a Synchronous motor is operating satisfactorily, the current in the armature phases should be about equal when the rotor is turning slowly. Trouble in the field winding such as an open-circuit causes a shut-down or excessive armature heating. When the current seems excessive, a test should be made for the polarity of the rotor coils or the reversal of the connections. When a Synchronous motor fails to show normal starting torque, and does not carry the proper load, the trouble frequently to be found is the *Open-circuit in the field circuit*, or the *reversal* of one or more field coils.

696. Troubles with Wound Rotors :—

Cause (1).—Faulty starting switch. Resistance inserted in the running condition.

Remedy.—Motors with wound-rotors are especially designed to have resistance inserted in their rotor circuit on starting up.

In the absence of a starting resistance, the motor will refuse to operate successfully, or start at all, unless a tapping transformer or compensator is used. On the other hand, if defective switch or faulty operation puts resistance in the circuit in the running condition, the motor slows down, and finally stops, probably burning out some resistance coils.

Cause (2).—Short-circuit in the starting switch produces a reduced starting torque, causing the motor not to start itself.

Examine the starter for grounds or short-circuit by usual drop or resistance tests.

Cause (3).—Rotor winding defective, due to break in one phase, wrong connections or reversals of phase-windings.

Remedy.—A break in one phase renders the motor equivalent to a single-phase one and thus incapable of starting itself (except in the case of the three-phase delta-wound starter. Wrong and reversed connections in the windings render operation very bad and unsatisfactory. A short-circuit in coils shows up itself by excessive local heating or smell of burnt coil.

Cause (4).—Collector ring troubles, due to dirt, rough surface of rings, wrong brush tension, bad contact, etc.

Remedy.—The existence of such defects causes excessive heating of the collector rings, and the contact resistance thus introduced in the rotor may reach high enough to affect the speed of the motor to a marked degree.

Clean and bed brushes. Clean and grind rings or turn them true. Adjust spring tension and see that the brushes work freely in the holders. (See D. C. machine "Sparking").

Cause (5).—Defects in pig-tail connections, due to bad connections, or want of fastening at binding screws.

Remedy.—The resistance between the brushes and the rotor resistance coils is increased by this fault and this causes the speed of the motor to go below normal.

697. Faults Common to all kinds of Motors :—

I. Rotor Fouling Stator :—

Cause.—Defective or worn-out bearings, causing rotor to touch or strike against pole-pieces.

Remedy.—To secure high efficiency, the air-gap between the rotor and the stator should be made very small, (so small as 1/50 in.). In such a case, a slight wear in the bearings soon displaces the rotor from the magnetic flux, and producing excessive friction and heating of rotor bars, great overload with probable pulling up of the motor.

Replace the brushes by new ones or raise the bearing pedestal. If impossible, adjust the end case properly, so as to effect a cure.

If the wear is very slight, especially in the case of ball bearings, these measures will prove of exceptional value for the trouble. (See above "Faults due to Bearings.")

II. Hot Bearings :—

Cause.—Bad, dirty and insufficient oil, faulty oil rings, grit or other foreign matter in bearings, etc.

Remedy.—Examine oil-cups ; strain oil of dirt or grit, or supply sufficient good mineral oil. Remove and clean oil rings, bearings, shaft, etc. very carefully, and then reset, clean lubricating oil being again introduced.

III. Stator Faults :—

Cause.—Bad insulation in windings due to moisture, oil or mechanical injury.

Remedy.—In an induction motor, the stator bears the same relation to the rotor as the primary of a transformer does to its secondary. So, if under faulty or excessive conditions, one is affected heavily, the other is also liable to be affected to the same extent, generally the stator being the first to give out under such circumstances.

Test the insulation resistance of the windings, determine the exact fault and correct accordingly. (See under "D. C. Armature and Field Troubles.").

IV. Other Faults in Windings :—

Cause.—Wrong or reversed connections in windings, damage due to mechanical faults, etc.

Remedy.—These cause the machine to start with excessive unbalanced currents, producing too much heat and peculiar noises. Motors may run at low speed or erratically, and lamps may burn dimly and flicker.

See if the clearance between the rotor and the stator is uniform and examine belt tension, stator coils and the starter itself.

Try if the rotor can be turned easily by hand, if not, examine the bearings.

Test for wrong or reversed connections in the windings or other faults to which the defective operation of the machine is due ; correct these as under the various heads of D. C. machine troubles.

The following table shows the behaviour of different types of induction motors with one or two lines or phases open :—

V. *Effect of Open Circuit in Stator Windings or Line of Induction Motors.*

Type of Motor	Open Circuit in Stator.	Open Circuit in Line.
Single-phase	Would refuse to start, but would continue to run in either direction if started, if only the starting winding was broken.	Could not possibly run.
Two-phase, three or four-wire.	Converts motor to S. P. motor. If running, would continue to run on light-load. Would pull up on heavy load and not be self-starting.	Break in any single wire renders motor somewhat similar to S. P. motor.
Three-phase	Open circuits in one-phase converts motor to S. P. motor, and it would continue to run on light-load, but pull up on heavy load.	One line-break converts to S. P. motor operation impossible.

Type of Motor.	Open circuit in Stator.	Open Circuit in Line.
	Open circuit in two phases, if star-connected renders operation of motor impossible. Open circuit in two phases, if mesh-connected may allow motor to run as S. P. motor, but it would operate in jerks.	Two line breaks render operation impossible.

VI. Three-Phase Motors with Wound-Rotors may have the following defects in the windings :—

(1) Open-circuit in one or more rotor coils.

(2) Open-circuit in one or more coils or phases of stator.

(3) Short-circuit in part of rotor winding causing excessive heating.

(4) Armature winding correct, but field coil or phase reversed.

If an open-circuit or break occurs in the field or stator of a three-phase motor, current will flow only in two arms of the winding, the other arm being rendered inactive by the break. Under such circumstances, the motor will have zero starting torque, but if started by hand, it would speed up gradually and work up to about 2/3rd full load capacity. (See " D. C. Motor Troubles.")

VII. Defects in Compensator or Auto-Starter Switch :—

Auto-starters are generally used for starting A. C. motors of the Induction type (when the motors are about 5 H. P.). Smaller motors are thrown directly on the lines without any starting device. As a rule, polyphase induction motors upto 5 H. P. are thrown directly on line ; motors from 7·5 to 30 H. P. are started by means of star-delta switch which is not an induction starter but simply a switch operating in oil and changing the connections of the motor from star on starting to delta on running. The motor in that case is provided with six terminals to accommodate the change. *Auto-starters* or *Auto-transformers* are mostly used for squirrel cage induction motors of considerable size or over 30 H. P. Auto-starters possess not only some resistance but considerable reactance for damping the current flow. The auto-starter has but one step from starting to running and the handle should always be thrown promptly from one position to the other position. In it, six wires are brought out to the rocker cylinder of the switch handle. One wire is a feed or line wire, the wire next goes to the motor, the next wire is the line and the next again to the motor and so on. When the switch is thrown to the starting position, the six contacts on the switch cylinder rocker meet six contacts on the starting block through one coil of reactance, and back to the next contact on the switch cylinder and thence to the motor. When the handle is thrown to the running position, only these contacts on the switch cylinder make contact,—these are the motor contacts on the switch cylinder and they meet the three contacts on the running block, which contacts are directly connected to the line wire either through the fuses or through overload relays. The line contacts on the switch cylinder, when the switch is thrown to the running position, do not contact anything they stand clear or dead-ended. These contacts on the switch cylinder can be identified by using a lamp blank and making contact with them, the switch handle being in the off postion ; a light between the line and line will be obtained.

Cause.—The *first trouble to look* for is burnt or imperfect contacts.

Remedy.—After taking the oil-pan off, the switch contacts can be inspected without trouble. If the contacts are burnt or rough, they should be taken off and filed smooth or replaced with new ones. The same applies to the fingers that meet the contacts. The handle should be thrown to one position and then the fingers should be tried to see that they press firmly and even against the contacts on the switch cylinder. If they do not, throw the switch handle to the off position and they can easily be bent inward sufficiently to make a firm contact.

In regards to the *broken wires*, the wires, those are attached to the switch cylinder, six in number, are bent every time the switch handle is moved. These wires now and then break down. The other six wires that enter the auto-starter go to the fixed unmovable contacts and rarely cause trouble. Test everything out as far as possible with the lamp blank. It is always to be remembered that a ring obtained with a magnet or a light obtained with a lamp blank is not always conclusive. When it is decided that the wire is broken, take out the two screws that hold that particular contact to the switch cylinder and pull down the terminal with a pair of pliers.

Cause (2).—Wrong connections at switch, causing motor to start on full voltage and take excessive starting current.

Remedy.—In this case, the motor generally slows down, accompanied by reduced operating torque and voltage, when the switch is thrown over to the second contact.

Remove the trouble by correction of the obviously wrong connections.

If the connections are correct, and still the motor takes excessive current, better try a lower tap on the compensator. Choose the best position which just provides the motor the necessary starting torque under normal load with the least disturbance on the line.

The following method of insulating the leads of auto-transformers will prevent the syphonising of the coil :—

(1) Remove the insulation from each lead just above the highest oil level for a distance of about 2 in.

(2) Sweat the stands of the cable thoroughly together so as to close up all spaces between the conductors for a distance of about 1 in.

(3) Insulate the lead with treated cloth tape, wrapping the tape tightly around the conductor and brushing each layer with insulating varnish.

(4) Extend the wrapping of the tape to three overlapping layers of at least one inch on the insulation at each end of the bare section.

VIII. Motor Stops when Partially Loaded :—

Cause (1).—Wrong connections at compensator.

Remedy.—Change and make connections correctly.

Cause (2).—Wrong connections of windings.

Remedy.—If a delta-wound stator be wrongly connected in Y-fashion, the motor may start up correctly on light load, but slows down as the load is increased.

When the six terminals of the stator winding are available, connections may be easily changed from Y to Δ.

Delta-wound motors for low-voltage supply may be connected to high-voltage lines by changing their connections from Δ to Y. Thus, a 220-volt, delta-wound motor would suit a 400-volt supply when its connections are altered to star-grouping.

IX. Bearing Faults, Oil Leakage, etc. :—

Cause (1).—Worn out bearings, causing rotor to foul stator on account of very small air-gap

Remedy.—See " Rotor Fouling Stator."

Cause (2).—Leakage of oil due to which oil may creep along shaft to windings eventually effecting a new break-down of insulation.

Remedy.—Worn-out bearings, excess of oil in reservoir, absence of oil throwers, etc., may produce leakage. The draught caused by the machine when in operation, may also suck the oil along the shaft.

A very effective measure to prevent oil creep is to make a groove $\frac{1}{8}'' \times \frac{1}{4}''$ of the spilt or sleeve type near the edge of the bearings, and then drill holes through the bottom of these grooves for the oil to run back into the well.

X. Improper End-play of Rotor :—

Cause.—In order that the rotor may run in the magnetic centre with respect to the stator, it is always desirable to allow a slight end-play to it. In the absence of limited allowance of this free end motion, the rotor in its attempt to centralise itself by the magnetic pull of the stator, will exert a continual thrust on eve end of the bearing, producing excessive heating and perhaps shutting down of the machine.

Remedy.—Test this by pushing at the centre of the shaft at one end with a piece of wood whilst the machine is running. Under faulty conditions, it will be possible to move the rotor easily when pushed from one end, whilst at the other, no movement is possible

If possible, try moving the rotor bodily along the shaft in a direction towards the hot bearing—a slight movement may suffice. Knocking over the teeth with a piece of wood and mallet a little, (say 1/8 or 3/16 in.) towards the hot bearing may also effect a cure. (See "Heating of Bearing" under D. C. Machine Troubles.)

XI. Flashing over Collector Rings or at End Connections of Field Coils in Starting Synchronous Motors :—

Cause.—Excessive voltage induced in the field winding, due to low resistance, as the motor starts up.

Remedy.—During the speeding up period this fault is shown up by a bad flash or several flashes appearing together across the rings or end-connections of the field coils. A reduction of the abnormal pressure, (which may often rise as high as 3,000 volts) may be effected by inserting a properly designed resistance to largely increase the value of the field circuit resistance.

(For similar troubles with a commutating machine see "Flashing around Commutator, etc")

XII. Inspection of A. C. Motor Installations :— The chief points which a skilled attendant must observe at the installation are,—

(1) Voltage—if normal at motor terminals.

(2) Loads—not increased beyond maximum output.

(3) Condition of bearings; quality and quantity of oil; slip-rings, brushes, etc. are if working properly.

(4) Air-gaps - if uniform all round.

(5) General cleaning of commutator, brushes, brush-rings, rheostat studs and all protecting switch-gear.

XIII. Causes of A. C. Motor Fuses Blowing off :—In addition to the overload on the motor, many other things cause the fuses to blow out. The following causes and symptoms have been described by Mr. Henry Zeuner W. of the Milwaukee (Wis.) Electrical Light Company in his articles in Elec. World September 20, 1919.

(1) Operator throwing off the starting switch of the compensator (Auto.) from starting to running position too early.

(2) Operator throwing the switch to the running position even without touching the *start*-position.

(3) Motor winding becoming grounded.

(4) Excessive current due to low voltage, short-circuits in the stator windings, single-phase operation. etc.

(5) Starting switch being in running position when the service comes back on the line after interruption.

Wound rotor motors or squirrel cage motors which are not protected by a no-volt coil may be shut down at any time because of the last mentioned cause. To overcome the trouble, a group of motors is protected by an oil-switch equipped with no-volt release. The arrangement has a disadvantage, that whenever the oil-switch opens, it becomes necessary for some one to go round and open each individual motor switch before the oil-switch is closed for the second time. A ground may blow only one fuse and leave the motor operating from one-phase of the line. When a poly-phase motor runs single-phase it not only gets hot but makes a growling noise which is specially noticeable under heavy load. The motor will slow down to about half the speed also. By the time

this symptom shows the probable cause of trouble, and it is decided to shut down the motor, a second fuse is sometimes blown off by excessive current per phase. If only first defective fuse is replaced the motor may be started from the line side of the switch which is connected ahead of the fuses. When the switch is thrown over to the running position, the motor runs as a single-phase motor and the same troubles again arise, and so we may think that the motor is spoilt; but if we had tested all the fuses in the first instant and replaced all burnt-out fuses instead of only one of them, we would have put the motor back to service without any loss of time. Low voltages also cause the blowing of the fuse, as it causes the excessive current to flow and burn the stator coils. The voltage is checked by test lamp.

XIV. Testing Motors for Grounds:—When testing an A. C. motor for grounds, a magneto or high-voltage testing transformer should be used as the line-voltage will seldom show a ground unless it is making a very good contact. As a rule, the motor frames should be grounded. If they are insulated from the ground, the motor can be kept in operation with one phase grounded to the motor frame but defect should be remedied immediately. A second connection between the secondary windings and the motor will burn out the coils which it short-circuits and if not given proper attention, the two grounds may entirely burn away the whole winding. When both the supply system and the motor frames are grounded, as is usually the case, one ground on the stator winding will blow one of the motor fuses, unless the fuse is too heavy, in which case, the ground may burn out some of the coils. If the test is made, the wires leading to the motor may be found grounded. It is good to test the motor while running. Under such conditions, the speed should be tested. *Low speed* and *inability to pull the load* are usually the indications of *bad connections* between the rotor bars and rotor end-connections.

XV. Shaft Currents in Electrical Machines and Remedies Thereof:—A common source of trouble in revolving electric machines is the presence of electric

currents flowing across the rubbing surfaces of the bearings. These currents make their presence known by blackening the oil, pitting the bearing, and, in some cases, scoring the shaft. The usual type of shaft current flows in a circuit consisting of the shaft, the bearing pedestals and the base. Interruption of this circuit by insulation under the pedestals is the most usual method of avoiding trouble from this source. This has been done both at Bangalore and Sivasamudram stations.

Possible Causes of Shaft Currents :—All shaft currents are due to the existence of an electromotive force between the shaft and bearing lining. This E.M.F. can be produced either by : (*a*) a direct or alternating flux flowing in the shaft, (*b*) a difference of oil potential between shaft and ground due to electrostatic effects or to grounding of the rotor conductors to the core, or (*c*) an alternating flux linking the shaft.

698. Diagnosis of Motor & Generator Troubles :—Now we shall look to the troubles that are usually found and come across in motors, generators etc. in D. C. as well as A. C. machines. The troubles have been treated as troubles themselves not giving the situation in which it or they occurred.

The troubles which are usually found can be traced to the main two causes (*a*) Faulty operation, (*b*) Mechanical or Electrical defects..

The factors of Faulty operation may be again subdivided as follows :—

(1) Lack of proper cleaning, (2) Operation in damp places, (3) Exposure to acid fumes, gases etc., (4) Lack of occasional routine inspection and negligence in replacing the worn out parts, (5) Operating temperature too high.

Taking each of the above items one by one :—

(1) **Lack of Proper Cleaning** :—Lubrication is the proper and chief requirement of the moving parts in a machine. This oil, though confined to the parts needing lubrication, makes its way to the other parts as well. In motors and generators the oil which is allowed to accumulate on the winding has a detrimental effect on the

insulation and is a frequent cause of a heavy short-circuit, and ground. It also accumulates dirt and dust and chokes the passages of ventilation. This results in the increase in the temperature of the parts involved. Frequent cleaning at regular intervals is chiefly needed. Motors operated in dirty places should be blown daily with compressed air.

(2) **Operation in Damp Place** :—The materials chiefly employed for insulating purposes are mica, paper, cotton tape and cloth. Excepting mica all of them absorb moisture. Where the motor is not continuously running, the moisture reduces the strength of the insulation to the rupture point resulting in all sorts of troubles. For use in such places, special types of designs should be asked for. The provision for heating up the windings and insulation when the machine is to stand idle should be provided. This can be very economically obtained by using lamp boards.

(3) **Exposure to Acid Fumes and Gases** :—As in the case of oil and water, the acid fumes destroy the insulating strength of most of the insulating materials; they also attack the metal of the machine and cause commutator troubles. If the motor or generator is required to be used in such places, specially insulated windings should be provided. Machines operated should be cleansed more frequently than required in any other condition. The commutator must be wiped daily with a little vaseline.

(4) **Lack of Frequent Inspection and Replacing the Damaged Parts** :—Short-circuits and grounds are frequently traced to rubbing of the motor winding with the field poles, caused by a bent shaft or worn out bearing. A loose fit of the commutator on the shaft, when it has been replaced after a job, may result in sufficient movement to break off the leads of the armature coils at the neck (Risers) of the commutator. The resoldering of such a defect does not cure the trouble. In this case, it will probably call for a new shaft. The roughness of the commutator, the high mica and the air-gap of the machine should be frequently checked. If possible, a

record should be kept. A frequent check for the proper play of the shaft in the bearing will prevent the grooving of the commutator which might be thought to be due to unsuitable brushes.

(5) **Operating Temperature too High** :—The standard temperature for different kinds of insulating materials according to A.I E.E. for cotton, silk, paper-impregnated, enamelled wire is 105°C or 221°F. For mica, asbestos, in which former materials are used, will be 125°C or 257°F. All parts of electrical machinery, other than those whose temperature of the insulating materials may be operated at such temperatures, may not be injured in any respect. But no part of continuous duty machinery subject to rough handling in operation such as brush rigging shall have a temperature in excess of 100°C (212°F) for more than a very brief time. Unless the surface temperature of 176°F is reached, there is a little danger of injury to the insulation.

699. Flickerings of the Lamps :—

Cause (1).—Uneven running of engines—probably governor not working properly.

Remedy.—Examine and overhaul the engine, specially the governor.

Cause (2) —Loose connections either on machine or on switch-board or external circuit.

Remedy.—Examine all the connections and see that they are all firm and make good contact.

700. General Repairs :—

Grinding of the Commutator :—

The tools required and the grinding operations are quite simple.

The first thing to do is to remove all the brush-holders and connecting segments of the rings of connections from the end shields. Now on the base plate a special screwed hole is provided just opposite the commutator to fix the grinding machine stand. On to this screw is fixed the ratchet which is a simple cast iron table just of the lathe table type. On this table at one end is fixed a small

motor to turn the grinding stone which is on the spindle of the motor. The stone can be moved laterally as well as longitudinally by means of a square threaded screw just like the leading screw of the lathe.

After fixing up the ratchet stand & the motor, the first thing to be done is fixing the position of the grinding stone. This is done by means of an iron or brass needle which is fixed in the motor spindle instead of the grinding wheel. This needle is of the same radius as the stone. Now the needle is moved along the length of the commutator quite in the horizontal position and just grazing the surface throughout the length. When a suitable position is arrived at, the needle is taken out and the stone fixed in its place, and the actual grinding process thus begins.

The machine is now made to run slowly but applying only the voltage for a very short time and then allowing it to run only on the force of the momentum thus acquired. Now the motor of the grinding stone is started and the grinding stone just brought near the surface of the commutator; slowly the operator has to move the grinding stone longitudinally throughout the length of the commutator, and repeating the same till the stone takes off only a little metal uniformly throughout the length of the commutator surface. If this operation is satisfactorily finished the rough grinding stone should be replaced by the finer one and the same procedure should be followed again.

This repeated procedure is to be followed till the perfect smoothness all over the length of the commutator, is obtained. Sometimes, only the part of the surface length requires grinding. This gradual grinding can be compared with the final scraping, done with a scraper to make a perfect plane after the filing work is finished. When the part required to be ground is properly brought to the level of the whole length, the stone should be slowly made to move throughout the length to see that at no part it touches the surface. Thus patiently and calmly the grinding is to be proceeded with.

The next job is to rub the surface by means of different grades of carborandum cloth, to polish the surface of the commutator. For this, a special wooden block to fit the commutator is prepared.

This is rubbed over the surface of the commutator when the machine is rotating very slowly.

The next thing following is to under-cut the mica. Due to grinding-stone process etc., mica might have come in the same level as the copper bars and the particles of copper might short-circuit the two bars; so the mica insulation between the two bars requires to be cut or rather sawed out to a particular depth, taking care all the while not to injure the finished surface of the commutator. Sawing is done by means of a small blade saw about $4'' \times \frac{1}{2}''$ attached on a rectangular block at two ends by means of the screws. This rectangular block, which is also of the same length as saw and of thickness about $\frac{1}{2}''$ and height also the same, acts as a sliding guide to the saw in the particular groove. The iron block slides over the copper bar and the blade in the groove.

The blade is made to move in one direction only as otherwise it may go crosswise and injure the copper bars during the reverse drive.

After the under-cutting, the mica is finished, the copper surface between the two bar surfaces is slightly raised out due to sawing and this is to be scraped off lightly by means of a hand scraper.

This finishes the job of grinding the commutator surface.

Now if other repairs are not necessary, we fix up the brushes etc. in position, make the proper connections and then heat up the machine to remove the dampness, or otherwise the machine will not start. This heating is done by means of cluster lights placed inside the spider, end-shields etc. and the whole machine covered by tarpaulin.

After the proper heating is finished, the machine is started without applying load on it and allowed to run for 5 to 6 hours. Then for next four hours the machine is

loaded with only 25% load, and the next loading after this period should be of 50% for another 4 hours and then the full load may be applied.

The surface of the commutator *should be rubbed with the petroleum rag* at least every two or three hours to avoid the chattering of the brushes ; this helps to keep the carbons in the healthy condition as well as the commutator surface.

Changing and Cleaning of the Brushes :—

When the grinding of the commutator is in progress the brush arms that were disconnected are properly cleaned with scrapers, sand papers and petrol. Every screw and bolt requires to be removed and properly cleaned because this job is not a frequently occurring one. The carbons are also changed and some old ones which are possible to be used over again are properly shaped and used. The carbon holders and the springs are properly cleaned. When this cleaning process is finished and the commutator is ready to receive the brushes, the brush-holders are assembled in their proper place.

Water Resistance :—

Occasionally the water resistance, which is used for starting purpose, requires to be looked after, and this is done several times during the year. Here we have to clean the solution off the scum that has formed on the top of the water-level. This is removed by means of a small spatula specially made for the purpose. See the condition or ascertain by experience if some more soda-ash requires to be added up from time to time to maintain the strength of the electrolyte. Any scale or rust formed on the handle should be removed carefully. Connections should be examined regarding the firmness ; and the bottom wooden support should be also examined as often as possible that they are not damp in the rainy season.

Cleaning the Switch Boards :—

Simple dusting out is of course done daily by the attendants but the internal cleaning of the closed chambers should be done at least once every 3 months if

possible, otherwise, every six months at the most. For this purpose, every second sunday of every month is set aside. On this day different parties of coolies under one supervisor will proceed to different sub-stations or service-stations and after isolating the panel will open out the panel after preliminary dusting out the whole thing.

701. Winding Defects :—

The following faults and remedies are intended to show the cause and cure of troubles resulting from wrong connections in a motor which has been totally rewound, partly rewound, or reconnected in any way. It is usual to test a motor in the shop before it is assigned to duty. Winding defects may be classified under the following headings :—

(1) Grounds.
(2) Short-circuit within a coil.
(3) Short-circuit of a complete coil.
(4) Short-circuited pole-phase group.
(5) Open circuit.
(6) Reversed coil.
(7) Reversed pole-phase group.
(8) Reversed phase.
(9) Wrong grouping.
(10) Wrong connection for a given voltage.
(11) Wrong speed and number of poles.

1. Grounds :—Grounds are usually caused in a new winding or in a repaired winding by careless handling or insertion of coils in the slots. After inserting each coil in a slot, it should be tested for ground, using either a megger or a bank of lamps. If however, a motor which tested O. K. becomes grounded after being connected, due to rough handling, it may be necessary to use the "Smoke Method" to discover the ground. This consists of impressing a higher voltage than normal on the windings. The connection between the windings and frame at the ground will become hot or will arc, and the ground is usually found without much trouble. If however, it cannot be located by this means, passing a heavy current through the windings may locate it. On an ungrounded system and where no other equipment is

grounded, a single ground on a motor will cause no damage. But on a grounded neutral system a ground on a star-connected motor will cause an unbalance in the phase currents, with heating. A ground has little effect on a delta-connected motor on a grounded neutral system unless another motor in close proximity to it is also grounded.

2. **Short-circuit within a Coil**:—This is generally due to two layers getting crossed and wedged. A coil thus affected becomes hot if used with normal voltage even if there is no load on the motor. This kind of defect can be located by means of an exploring coil. The exploring coil consists of several turns of magnet wire wound around a core of several layers of sheet iron or steel. The coil is excited by a low alternating voltage and constitutes the primary of a transformer, the secondary of which is any coil of the winding to be tested. The short-circuited coil will be noticed by a heavier current flowing in it and by the increased heating. If a small piece of soft iron is placed over the side of the coil under test, it will vibrate if the coil is short-circuited. The same method is used where a whole coil is short-circuited at its connectors.

3. **Short-circuit of a Complete Coil**:—A whole coil is short-circuited by having its two ends wrongly connected together or to a group connection. The only symptom is that it is hotter than the rest.

4. **Short-circuited Pole-Phase Group**:—About the way in which a whole group can be short-circuited is by closing the group when making the phase end connections. A defect of this kind is indicated by the group becoming hotter than the remaining groups when voltage is applied to the windings. The defect can be found by means of the exploring coil.

It is more readily found by the Compass Method. In order to use the compass test, the stator must be excited with direct current. The use of D. C. gives each pole a set polarity, while with A. C. the poles are continually changing when the windings are excited, the compass is moved around inside the stator core, and as each pole is approached, the polarity is indicated by the compass.

If the North seeking end of the compass needle is attracted, it will denote a South pole, and *vice versa.*

In testing a star-connected three-phase motor, the D.C. is impressed on each of the phase leads, and each phase tested separately, and the polarity of each pole marked. In testing a delta-connected three-phase motor, one of the delta-connections is opened.

5. Open Circuit:—An open circuit, in either a two-phase or three-phase motor with series-connected windings, is indicated by the motor standing still and humming; in other words, it acts as if trying to run single phase. It is a simple matter to locate the trouble in a star-connected three-phase motor, as a magneto connected to the various phase leads will indicate which phase is open. With a delta connected three-phase motor, however, the current, still has a path, even when one phase is open. It is therefore, necessary to open each delta until the phase with the open circuit is located.

Starting at any group, which can easily be determined by the taped ends, each group should be marked with chalk, each phase having a different colour. After the groups are seggregated a test set is used to locate open coil or group. One lead or terminal of the set is connected to a motor terminal while the other terminal, is forced through the insulating tape at the end connections. The test circuit need only be 110 volts which requires only one lamp. Starting at the group nearest the phase terminal, each group connection is touched with the awl until one is reached where the lamp does not light. The coil end just touched and the one preceding it in the test are the ends of the open circuited coil.

6. Reversed Coil:—In connecting a group of coils, the bottom of one coil is connected to the top of the one next to it, and so on. If coil *A* is connected properly to the balance of the coils and groups of its phase, coil *B* will be reversed as regards polarity. In locating a fault of this kind, the Compass Methed is used. This test is carried out in the same manner as for short-circuits, but the result of the test is different. Instead of getting no deflection of the compass needle, the needle will indicate a reversed polarity, when placed over the reversed coil.

7. Reversed Pole-Phase Group :—When a motor is connected adjacent pole, it sometimes happens, that in leaving one group for the next, the next group is not crossed, and consequently, the polarity of the two groups is the same. A fault of this kind is located by the Compass Method.

8. Reversed Phase :—Where one pole-phase is reversed, the fault shows up by the unusual behaviour of the motor. The speed is affected that is, reduced to almost nothing if the motor starts at all. There will be a groaning sound and the temperature increases rapidly.

If one phase of a 3-phase motor is reversed, either star or delta, the reversed phase bucks the remainng two. Normally connected, the phases are 120° apart, while with one phase reversed, the reversed phase is opposed 60° only from the other two. The reason for this is that the counter E. M F. in the reversed phase is 60° from the other two. In order to correct the fault in a star-connected motor, the reversed phase is opened at the star, the end of the phase winding originally connected to the star is made one of the motor leads, while the original lead or terminal of this phase is connected to the star.

9. Wrong Grouping :—The number of slots per pole-phase group is found by dividing the total number of slots by the sum of poles times the number of phases. In connecting a winding, the groups should first be counted and marked. When there is a mistake the currents will be unbalanced in all the three phases.

10. Wrong Connection for a Given Voltage :—The effect of wrong voltage impressed on a winding is usually easily deteced. If the motor becomes hot and hums excessively at no load, it shows that the voltage is too high, the speed being normal.

OPERATING TROUBLES.

The main troubles occurring in the operation of polyphase induction motors are given in tabulated form in Table II together with the symptoms, cause and remedy.

Symptom 1 :—Oil is sometimes siphoned from the bearing well, due to the windage of the motor, and as a usual thing motor manufacturers guard against this fault.

Symptom 3 :—This symptom will sometimes lead the operator to believe the motor is trying to run single-phase as if the rotor is almost touching the stator, the motor, if a high speed one, may not start when connected to the line.

Symptom 4 :—This symptom will show up in both troubles (*a*) and (*b*), the effect being practically the same. If the trouble is due to a short-circuit in one or more coils of one-phase, the winding in that phase is much less, with the result, that a greater current will flow in that phase. The remedy is either to replace the short-circuited coil or coils, which by the way is the only real and lasting remedy or to jump the damaged coil or coils.

When one phase of a poly-phase motor is grounded, there is little or no effect on the motor if the system is ungrounded and no other ground exists on equipment in close proximity to it. On a grounded neutral system there is a little or no effect when one phase of a delta-connected motor is grounded ; and since in a Δ-connected motor the voltage in any phase at any instant is exactly equal and opposite in effect to the other two phases combined, the current in any phase equals the sum of the currents in the other two at any instant, so that no matter in what part of the winding the ground occurs, the unbalance of current will be slight if the motor is not overloaded.

Symptom 5 :—This is probably the most common fault occurring in poly-phase induction motors, as the trouble is not always apparent at a glance. A poly-phase induction motor will run single-phase indefinitely, once it is up to speed if not loaded beyond the point where it will burn out. The reason why two phases of a star-connected motor and only one phase of a Δ-connected motor become hotter than the others may be easily seen.

Symptom 6 :—The trouble, cause, and remedy for this symptom is somewhat like symptom 4 with the difference that in this case, the seat of the trouble is more

easily found, since fire is usually seen at that point. If the location is not readily found, passing a current through the stator windings with the rotor removed will readily locate the fault.

Symptom 8:—A trouble of this kind is usually caused from moisture which forms a path between the various windings due to the breaking down of the coil insulation. While the motor may be placed back in service by cutting out the damaged coils, where there are not too many, it is a better practice to lift the coils and replace them with new ones.

Note :—For an arc to persist, it is necessary to have a certain potential, *i. e.*, the arc pressure e. At any moment, the arc therefore absorbs the amount of power equal to $e \times i$ where i is the instantaneous value of the current flowing. The energy w expended during the time t_1 the arc lasts is

$$w = \int_0^{t_1} e\ i\ dt$$

This is called the arcing energy and represents the electrical energy which is converted into heat, mechanical and chemical energy during the rupturing process. These three forms of energy are the causes of the undesirable occurrences accompanying the arc. The energy is a measure of the dilatorious effects of the arc. This should be kept as low as possible.

Troubles of Poly-phase Induction Motors.

Symptom.	Trouble.	Cause.	Remedy.
1. Bearing too hot to touch, or smoking.	(*a*) Bearing dry. ...	(*a*) Not sufficient oil ; oil rings not working.	(*a*) Refill with clean oil after first washing the bearing with kerosene.
	(*b*) Bearing dirty. ...	(*b*) Grit in oil. ...	(*b*) Refill with clean oil after first washing the bearing with kerosene.
	(*c*) Bearing tight. ...	(*c*) Insufficient oil ; oil rings not working ; grit in oil, causing particles of metal to be sheared off and deposited at other parts.	(*c*) Scrape bearing and shaft or replace bearing.

Symptom.	Trouble.	Cause.	Remedy.
	(*d*) Oil rings not working.	(*d*) Rings out of slots.	(*d*) Replace rings, making sure no metal adheres to sides of slot. If ring sticks or runs slowly, level it at either top or bottom with a fine file.
	(*e*) Bearing binding.	(*e*) Shaft out of true.	(*e*) Place shaft in a lathe and true and renew bearing.
	(*f*) Bearing out of true.	(*f*) Too much strain on pulley.	(*f*) Bearing should be shimmed with pieces of tin, as a temporary measure, or replaced with new bearing
	(*g*) Loose bearing	(*g*) Vibration ...	(*g*) Tighten set-screws holding bearing in journal.
2. Bearing hot, but no hotter, than other parts of motor.	Heat transferred from rotor or stator of motor.	Overload on motor	Decrease load or increase size of motor.

3	Smoke issues from windings; part of windings are hot while remainder is cool; wedges over coils are charred.	Displaced air-gap or rotor not centred in stator.	Bearing worn on one side.	If noticed before coils are damaged, re-aligning the bearing and inserting new wedges will correct the fault; otherwise coils will need to be replaced.
	Every second coil in a two-phase motor and every third coil in a three-phase motor are hotter than adjacent coils.	(*a*) Not enough resistance in phase which is hottest causing unbalanced currents in phase.	(*a*) One or more coils of one phase short-circuited within themselves.	(*a*) Replace short-circuited coil or "jump" the coil as a temporary expedient.
		(*b*) One phase grounded.	(*b*) Dampness or damage by foreign material.	(*b*) Remove ground by lifting coil and reinsulating, on ground not serious if motor is not overloaded, when delta-connected. If star-connected, there may be unequal currents between phases. If two phases are grounded, a short-circuit is the result.

Symptom.	Trouble.	Cause.	Remedy.
5. Motor runs hard and on examination, it is found the groups of two phases of the star-connected motor and the groups of one phase of delta-connected motor are hotter than other groups.	Motor running single-phase.	One fuse blown or one overload relay out of order.	Replace fuse or adjust relay and take ammeter readings of each phase.
6. Motor runs hot and explosions, accompanied sometimes by fire, occur in winding.	Temporary ground or short-circuit.	Due to dampness which causes circulating currents, between coils and between any coil and ground.	Bake motor until all dampness disappears, and dip or brush with insulating varnish. If coils are punctured, replace with new coils. If motor is needed at once, the punc-

			tured coils can be cut out, if not too many, as a temporary expedient. Replace short-circuited coils as they will usually be found badly charred.
7 Motor runs hot with all stator coils of the same temperature.	Motor usually overloaded.	Motor overloaded	Reduce load.
8. One or more phases hot in spots while cool in others.	Part of windings inoperative.	Short-circuits between adjacent stator coils.	Test each phase with an ammeter and if readings are high, reduce the load or increase the size of the motor.
9. Motor refuses to start with starter handle in starting position although the motor issues a humming sound.	(a) Motor tries to run single-phase. (b) Air-gap displaced	(a) One fuse blown or one overload relay out of order. (b) Bearing out of true.	(a) Replace fuse, or adjust relay. (b) Shim the bearing or replace with a new one.

Symptom.	Trouble.	Cause.	Remedy.
	(*c*) Open circuit in stator windings.	(*c*) Caused either from a short-circuit, which might puncture a coil or from rough handling.	(*c*) Insert new coil or "jump" the damaged one.
10. Motor starts and runs, but rotor heats up while the stator is cool.	Abnormal currents in rotor.	Rotor bars loose or grounded.	Tighten set-screws holding rotor bars to short-circuiting rings and solder or weld them, and remove grounds. In the more up-to-date types of rotors having cast-on end rings this trouble is seldom encountered.
11. Motor issues a peculiar sound when running light as if a heavy load were	One coil in one phase reversed.	Due to wrong connection when being repaired or reconnected.	Connect coil to its proper group and in proper polarity.

thrown on, periodically with a slight slackening of speed at these intervals.			
12. Motor issues a buzzing sound when fully loaded.	Loose connection on rotor bars.	Over-heated bars or rings.	Tighten set-screws holding rotor bars to short-circuiting rings and solder or weld them and remove grounds.
13. Motor loses power and speed when fully loaded.	Rotor out of magnetic centre in respect to the stator.	End-play all taken up at one end of shaft due to shifting of bearings; motor out of level; or if direct connected coupling driven too far on shaft.	Level motor; put bearing back where they belong; or move coupling until the rotor will float in the stator.
14. Wound-rotor motor runs at half speed.	One of the phases open in the rotor windings.	One lead to the collector rings broken off or damage to the rotor windings.	Test out for the open circuit and repair.

Care and Maintenance

Time of Inspection.	Bearings.	Motor-frame.	Motor windings.
Daily	Oil if necessary. See that rings are working. Feel for rise in temperature.	Examine ground wire.	Feel for excess heating.
Weekly	Examine oil and renew if gritty or darker in colour than usual.	Adjust end bells to centre the rotor if air gap is not of the same width at all points.	Blow out windings with compressed air or hand bellows, if motor is in a dusty place.
Monthly	Renew oil on all high speed motors and all other situated in dusty locations		
Tri-yearly.	Bearings should be drained and cleaned with kerosene and the oil renewed. High-speed sleeve bearings should be carefully examined and in most cases renewed. Ball bearings should be cleaned and greased.	...	If windings are subjected to corrosive elements, motor should be thoroughly cleaned and baked, windings re-varnished and again baked.
Yearly	Renew all bearings that are badly worn.	Frame should be cleaned with kerosene and painted.	All windings should be cleaned, varnished and baked.

of Induction-Motors.

Rotor.	Starter.	Switches and fuses.
See if there is proper end-play.	If in a damp place feel the oil tank. If hot, it denotes the presence of water in the oil.	
Use feeler between rotor and stator to find if rotor is out of centre.	Overhaul starter if motor is started and stopped frequently.	Inspect and clean if necessary.
...	Overhaul starters. ...	Inspect and clean.
Rotor should be cleaned; if wound rotor, it should be treated same as stator.		
Rotor overhauled	Oil should be changed in all starters.	Switch and fuse contacts should be renewed if badly pitted.

Standard Wire Gauge

Gauge Number S. W. G.	Diameter.		Cross-sectional Area,		
	Inches	Millimeters.	Square inches.	Circular mils.	Square mms.
1	2	3	4	5	6
0000	·400	10·160	·125663	160000	81·070
000	·372	9·4487	·108686	138384	70·117
00	·348	8·839	·095114	121104	61·362
0	·324	8·229	·082447	104976	53·190
1	·300	7·620	·070685	90000	45·603
2	·276	7·010	·059828	76176	38·597
3	·252	6·400	·049876	63504	32·176
4	·232	5·893	·042273	53824	27·272
5	·212	5·285	·035299	44944	22·772
6	·192	4·877	·028953	36864	18·678
7	·176	4·470	·024328	30976	15·659
8	·160	4·064	·020266	25600	13·035
9	·144	3·658	·016286	20736	10·507
10	·128	3·251	·012868	16384	8·301
11	·116	2·906	·010568	13456	6·818
12	·104	2·642	·008595	10816	5·480
13	·092	2·337	·006647	8464	4·288
14	·080	2·032	·005026	6400	3·243
15	·072	1·829	·004071	5184	2·627
16	·064	1·626	·003217	4096	2·075
17	·056	1·422	·002463	3136	1·254
18	·048	1·219	·001809	2304	1·167
19	·040	1·016	·001256	1600	0·8107
20	·036	0·914	·001018	1296	0·6567
21	·032	0·813	·0008042	1024	0·5189
22	·028	0·711	·0006157	784	0·3972
23	·024	0·609	·0004524	576	0·2918
24	·022	0·559	·0003801	484	0·2452

for Electro-Magnets.

Diameter double cotton covered.	Turns per linear inch.	Ohms per 1,000 feet.		Lbs. per ohm (bare) at 15°C.
		15°C	60°C.	
7	8	9	10	11
·412	2·427	·063633	·075345	7611
·384	2·604	·073575	·087117	5693
·360	2·777	·084068	099543	4361
·336	2·976	·096991	·11484	3276
·312	3·205	·11313	·13394	2408
·288	3 472	·13368	·15827	1725
·264	3·788	·16035	·18985	1199
·244	4 098	·18918	·22399	861·2
·224	4 464	·22600	26829	778·6
·204	4 902	·27670	32761	402·5
·188	5·319	32908	·38963	284·6
·172	5·814	·39784	·47104	194 7
·156	6 410	49059	·58085	128·1
·140	7·143	·62473	·73968	78 97
·128	7·812	·75878	90170	53·33
·116	8 623	94078	1·11387	34·82
·104	9·615	1·2029	1·4242	21·300
·092	10 87	1·5908	1·8836	12·178
·084	11·90	1·9639	2·3254	7·9966
·076	13·16	2·4856	2·9431	4·9834
·067	14·92	3 2465	3·8441	2·9240
·059	16·94	4·4202	5·2339	1 5773
·051	19·61	6·3664	7·5383	·76037
·046	21·74	7 8548	9·3006	·49951
·042	23·81	9 9429	11·773	·31173
·038	26·31	12·987	15·377	·18273
·034	29·41	17·675	20·928	·098651
·032	31·24	21·085	24·909	·069481

The figures in this Table apply to situations where 100°F. (37·7°C.). A margin in the maximum possible contingencies.

Gauge.	Section.	Rubber Insulated Cables.	
Number of wires and gauge in S. W. G. or inches.	Nominal cross-sectional area of conductors.	Current. Maximum current permissible.	Volts Drop. Approximate total length in circuit (lead and return) for 1-volt drop.
1	2	3*	3a
	Sq. ins.	Amps.	Yds.
3/25	0·0009	3·7	10
1/·036″	0·0010	4·1	10
3/24	0·0011	4·5	10
3/23	0·0013	5·3	10
1/·044″	0·0015	6·1	10
1/18	0·0018	7·2	10
3/22	0·0018	7·2	10
3/·029″	0·0020	7·8	10
7/25	0·0022	8·6	10
3/21	0·0024	9·5	10
1/17	0·0025	9·8	10
7/24	0·0026	10·4	10
3/20	0·0030	12·0	10
7/23	0·0031	12·4	10

*The currents in columns 3 & 4 are not always permissible, specially

the maximum temperature of the air does not exceed temperature of the cables has been allowed to provide for

Paper of Fibre Insulated Cables.		Resistance.
Current. Maximum current. permissible.	Volts Drop. Approximate total length in circuit (lead and return) for 1-volt drop (column 3*a*).	Conductor resistance in standard ohms per 1,000 yds. at 20°C.
4	4*a*	5
Amps.	Yds.	Ohms.
3·7	10	26·4
4·1	10	23·59
4·5	10	21·8
5·3	10	18·4
6·1	10	15·79
7·2	10	13·5
7·2	10	13·5
7·8	10	12·36
8·6	10	11·3
9·5	10	10·8
9·8	10	9·9
10·4	10	9·3
12·0	10	8·2
12·4	10	7·8

in lighting circuits where the determining factor is drop in volts.

1 Gauge No.	2 Section.	3* Amps.	3*a* Yards.
1/16	0·0032	12·9	10
3/19	0·0037	14·8	10
1/15	0·0041	16·3	10
7/22	0·0042	17·0	10
7/·029″	0·0045	18·2	10
1/14	0·0050	19	10
3/18	0·0053	20	11
7/21	0·0055	21	11
7/20	0·0070	24	12
7/19	0·0086	28	12
7/·044″	0·0100	31	13
7/18	0·0125	34	14
7/·052″	0·0145	37	15
7/17	0·017	40	17
19/20	0·019	43	18
7/16	0·022	46	19
19/19	0·023	47	19
7/·068″	0·025	50	20
7/15	0·028	53	21
19/18	0·034	59	23
7/14	0·035	60	23
19/·052″	0·0400	64	24
19/17	0·046	70	26
7/·097″	0·050	74	27
19/·058″	0·050	74	27
19/16	0·060	83	29
19/·072″	0·075	97	31
19/14	0·094	113	33
19/·083″	0·100	118	34
37/16	0·117	130	36
19/·092″	0·125	134	37

4* Amps.	4*a* Yards.	5 Ohms.
12·9	10	7·6
14·8	10	6·6
16 3	10	5·8
17·0	10	5 8
18 2	10	5·28
20·1	10	4·86
21 2	10	4·6
22·1	10	4·4
28	10	3·5
34·6	10	2·8
42	10	2 298
50	10	1·96
57	10	1·643
65	10	1·44
69	11	1·29
75	11	1·10
76	12	1·04
81	12	0·98
86	12	0·87
96	13	0·72
97	13	0 71
104	14	0 663
114	15	0·53
120	16	0·48
120	16	0 50
135	17	0·41
157	18	0·32
183	19	0·26
191	20	0·24
210	21	0 21
219.	21	0·197

1 Gauge No.	2 Section.	3* Amps.	3a Yards.
37/·072″	0·150	152	39
19/·101″	0·150	152	39
37/14	0·182	172	42
37/·083″	0·200	184	43
37/·092″	0·250	214	47
37/·104″	0·300	240	50
37/·112″	0·350	264	53
61/·092″	0·400	288	55
61/·097″	0·450	310	58
61/·104″	0·500	332	60
61/·108″	0·550	357	61
61/·112″	0·600	384	62
61/·118″	0·650	410	63
91/·098″	0·700	434	64
91/·101″	0·750	461	65
91/·108″	0·800	488	65
91/·112″	0·900	540	66
91/·118″	1·000	595	67
127/·101″	1·000	595	67

4* Amps.	4a Yards.	5 Ohms.
246	23	0·165
246	23	0·163
275	24	0·134
296	25	0·124
343	27	0·101
385	29	0·079
425	31	0·068
464	32	0·061
502	34	0·055
540	35	0·048
583	36	0·045
624	36	0·041
662	37	0·037
700	38	0·036
738	38	0·034
776	39	0·030
855	39	0·028
932	40	0·025
932	40	0·025

Approximate

This table does not take into account the lengths
forms a good practical guide as to the selection of fuses

Currents in Amperes	Tin Wire. Dia. in inches.	Tin Wire. Approx. S.W.G.	Lead Wire. Dia. in inches.	Lead Wire. Approx. S.W.G.
1	0·0072	36	0·0081	35
2	0·0113	31	0·0128	30
3	0·0149	28	0·0168	27
4	0·0181	26	0·0203	25
5	0·0210	25	0·0236	23
10	0·0334	21	0·0375	20
15	0·0437	19	0·0491	18
20	0·0529	17	0·0595	17
25	0·0614	16	0·0690	15
30	0·0694	15	0·0779	14
35	0·0769	14·5	0·0864	13·5
40	0·0840	13·5	0·0944	13
45	0·0909	13	0·1021	12
50	0·0975	12·5	0·1095	11·5
60	0·1101	11	0·1237	10
70	0·1220	10	0·1371	9·5
80	0·1334	9·5	0·1499	8·5
90	0·1443	9	0·1621	8
100	0·1548	8·5	0·1739	7
120	0·1748	7	0·1964	6
140	0·1937	6	0·2176	5
160	0·2118	5	0·2379	4
180	0·2291	4	0·2573	3
200	0·2457	3·5	0·2760	2
250	0·2851	1·5	0·3203	0

Fusing Currents.

between fuse terminals and other rating factors, but required in general work.

Copper Wire.		Iron Wire.	
Dia. in inches.	Approx. S.W.G.	Dia. in inches.	Approx. S.W.G.
0·0021	47	0·0047	40
0·0034	43	0·0074	36
0·0044	41	0·0097	33
0·0053	39	0·0117	31
0·0062	38	0·0136	29
0·0098	33	0·0216	24
0·0129	30	0·0283	22
0·0156	28	0·0343	20·5
0·0181	26	0·0398	19
0·0205	25	0·0458	18·5
0·0227	24	0·0498	18
0·0248	23	0·0545	17
0·0268	22·5	0·0589	16·5
0·0288	22	0·0632	16
0·0325	21	0·0714	15
0·0360	20	0·0791	14
0·0394	19	0·0864	13·5
0·0426	18·5	0·0935	13
0·0457	18	0·1003	12
0·0516	17·5	0·1133	11
0·0572	17	0·1255	10
0·0625	16	0·1372	9·5
0·0676	15·5	0·1484	9
0·0725	15	0·1592	8
0·0841	13·5	0·1848	6·5

INDEX.